Carbon Capture and Storage System Using Pinch Design Method

Renanto Handogo^{1*}

¹ Chemical Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya 60111, East Java, Indonesia

Abstract. Carbon capture and storage (CCS) have been investigated for a long time. It was intended to reduce carbon dioxide (CO₂) in the atmosphere due to fossil fuel combustion in power generation and industrial processes. CO₂ is captured and stored in various geological formations. The problem here is to match between source and sink such that alternative storage and unutilized storage capacities are minimum. Pinch Design Method as has been proposed by was used in this work. The concept is overwhelming that it can be used other than in the heat exchanger networks, such as in the water system design, mass exchanger networks and many other processes. Initially this concept was applied to carbon capture and storage but with no exact pairing between sources and sinks as proposed in this work using grid diagram as commonly shown in other processes. This work can point out the exact pairing between sources and sinks, and within the given time frame. A four different cases are investigated where the time difference between the starting time of CO₂ generated in the source and the beginning of sink availability. A value of 0, 5, 10 and 15 years are chosen to evaluate the amount of CO₂ that has to be stored and the amount of unutilized storage capacity. The case study has been prepared with 5 sources and 3 sinks. The result shows that the larger time difference the larger alternative storage and unutilized storage capacities. Therefore, having a shorter time difference will be more acceptable in the design CCS system.

1 Introduction

Global warming is an issue that is being discussed in the international world lately. Global warming is characterized by rising global average temperatures on the earth's surface. Studies show that the average global air temperature has increased by about 0.5 - 1.0° F (0.3 - 0.6° C) over the past century. This is the largest rise in surface temperature in the last 1,000 years and scientists predict a larger increase will occur over a century. This heating is mostly caused by increases in greenhouse gases, especially carbon dioxide (CO₂) and methane over the earth's atmosphere caused by the burning of fossil fuels, industrial activities, agriculture and deforestation. One solution that can be applied quickly and on a large scale is to use Carbon Capture and Storage (CCS) technology.

According to the ESDM Ministry, CCS is one of the climate change mitigation technologies that has the potential to reduce large-scale CO₂ emissions resulting from burning fossil fuels. CCS is an effort with a technique approach to capture carbon and store it in a safer form. This technology is a series of activities starting from capturing CO₂ sources such as natural gas processing facilities and power plants, then transporting

them to CO₂ storage locations in appropriate geological sinks.

Fig. 1. Ways of catching CO₂ from industries (post combustion, pre combustion, and Combustion) (IPCC, 2005)

In the CCS process, the process of matching between the source and storage of CO₂ are often subjected to various constraints, such as storage capacity availability, the location of the source and storage availability, and the time source and storage availability. These problems

* Corresponding author : renanto@chem-eng.its.ac.id

can be solved with a design technology that is pinch technology that can provide an minimum alternative and unutilized storage. Pinch technology is built on the laws of thermodynamic heat transfer. This technology is dominated by the design of Heat Exchanger Network (HEN) which provides optimum energy cost savings. The concept is overwhelming that it can be used other than in

the heat HEN, such as in the water system design, Mass Exchanger Networks (MEN) and many other processes. In water design system exactly cooling water system, the performance of a cooling tower is maximized by maximizing the inlet temperature to the cooling tower and minimizing the inlet flowrate. The role of the pinch technology here is for getting minimum cooling water flowrate (Smith, 2005). By MEN, we mean the systematic generation of a cost-effective network of mass exchangers with the goal of transferring certain species from a set of rich streams to a set of lean streams. A mass exchanger can be virtually any countercurrent, direct-contact mass-transfer operation that uses a Mass-Separating Agents (MSA) (eg, absorption, desorption, adsorption, liquid-liquid extraction, leaching, and ion exchange) (El-Halwagi and Manousiouthakis, 1989).

Initially this concept was applied to carbon capture and storage but with no exact pairing between sources and sinks as proposed in this work using grid diagram as commonly shown in other processes (Raymond et.al, 2013). This work can point out the exact pairing between sources and sinks, and within the given time frame. The pinch calculations in this work are performed with composite curve and Carbon Storage Cascade Analysis (CSCA). Just like in HEN, the composite curve CCS will consist of two lines, namely a source line as hot streams and a sink line as cold streams. By shifting the sink line until it gets pinch according to the set time difference it will get the number of alternative storage and unutilized storage.

Fig. 2. Concept of Cascade Analysis (Raymond et.al, 2013)

While the cascade analysis as shown in figure 2 is based on the cumulative amount of CO₂ load at a certain time interval from the first year until the last year. The biggest deficit in an interval is as alternative storage and the value is rearranged as surplus value at the beginning of the year so there is no deficit at each interval and will be obtained at a time with a value of 0 called a pinch.

The amount of surplus in the last year is as unutilized storage.

2 Study Description

2.1. Data Collections

Data collection is very important with respect to the reality of data in the field, as the success of the research results is influenced by proper data retrieval. Until now, in Indonesia the companies still have not implemented CCS system. Therefore, in order to obtain the data (case) which almost resembles the field situation, it is necessary to study literature as a comparison.

2.2 Create a Grid Diagram on Each Variable

The grid diagram is used to present the results of the Pinch Design Method.

3 Results and Discussion

3.1. Data Collections

From the study of literature, then in this study were given four variables namely dT (time difference) 0 years, 5 years, 10 years, and 15 years. The following data will be used in this research.

Table 1. Sources Data

Source	CO ₂ flowrate (Mt/y)	CO ₂ load (Mt)	Start time (y)	End Time (y)
1	15	300	0	20
2	5	150	0	30
3	5	150	0	30
4	20	400	20	40
5	10	400	30	70
Total	n/a	1400	n/a	n/a

Table 2. Sinks Data

Sink	Injectivity (Mt/y)	Storage capacity (Mt)	Earliest time available (y)	Characteristic end time (y)
1	20	900	10	55
2	15	750	20	70
3	10	550	30	85
Total	n/a	2200	n/a	n/a

3.2. Optimization Based on Multi Period

At each time interval, each source portion is combined into a composite curve section, by adding the line diagonally. Substitution of the composite part will start from the end of the previous section, which will be converted into a source composite curve. Similarly, the composite sink curve is also done the same as the source composite curve.

Fig. 3. Merging composite source and sink curves

In the figure 3, it shows that the relative position of the composite curve indicates an overlap between the source and sink composite curves. It is not possible in the real event, so it is called an infeasible region. Part of the composite sink curve is to the left of the source composite curve which means that the sink is only ready once the source is available.

Fig. 4. Merging composite source and sink curves with Pinch 0 year

The deficit may be interpreted as delaying the decision to capture CO₂, until internal sink time (storage) is readily available for use. Areas where the two composite curves overlap each other imply that 1100 Mt of CO₂ can be sent from source to available sinks. The composite curve shows that within 20 years the pinch point with the time difference is 0. In other words, the two composite curve encounters are at the pinch point. Further observation on the pinch diagram is the availability of a storage capacity of 1100 Mt which is not used as a sink from the source. Captured CO₂ of 1100 Mt presented that 50% of the 2200 Mt that can be stored in the 3 sinks. The same is shown by table 3 which is the cascade table for the 0 year difference show the pinch in the 20 year. The cascade table also show the same alternative storage of 300 Mt and unutilized storage of 1100 Mt.

Table 3. Cascade analysis for source and sink with 0 year time difference

t (year)	Source, S _{i,t} (Mt/y)	Sink, D _{i,t} (Mt/y)	Δt	Flowrate CO ₂ (Mt/y)	Load CO ₂ (Mt)	CO ₂ cascade (Mt)	
						Infeasible	Feasible
0	SR1 15 SR2 5 SR3 5					0	300
10		SK1 20	10	-25	-250	-250	50
20	SR4 20	SK2 15	10	-5	-50	-300	0
30	SR5 10	SK3 10	10	5	50	-250	50
40			15	15	150	-100	200
55			15	35	525	425	725
70			15	15	225	650	950
85			15	10	150	800	1100

Pinch point on the diagram divides the system into 2 regions. Before pinch point, there are areas where CO₂ requires storage. While after pinch point, there is excess storage. The above scenario is one of the problems that occur in this network, because almost all potential storage locations will experience some delay before the sink receives CO₂ from source. From figure 4 shows below the composite sink curve starts in the 10th year. In other words, alternative storage should be sought in the first 10 years of operation. If no external storage is available, then the decision to capture CO₂ must be suspended in the 10th year, when the internal storage is ready for use.

Fig. 5. CCS grid diagrams with 0 year Pinch time difference

Figure 5 shows that sink 1 receives CO₂ from source 1,2, and 4 in the 10 to 40 year timeframe. Meanwhile, CO₂ from partially source 2, and 3 is sent to sink 2 that ends up to year 70. Then sink 3 is receives CO₂ from source 5 in the 30 to 70 timeframe. From the grid diagram obtained the number of alternative and unutilized storage is suitable with the composite curve and cascade analysis calculations so that the pairing done with this grid diagram and resulted the exact pairing. However, in a plant occurring it is not possible to match pinch points with a 0 year time difference. From this research, discuss the optimization network with various time difference variables of 5, 10 and 15 years. This is based on real events in a carbon capture plant that

analysis calculations, so that the pairing can be done using this grid diagram and resulted in the the exact pairing.

Figure 10 is a scatter plot showing the relationship between Load CO₂ (Mt/yr) on the y-axis and Pinch on the x-axis. The plot is divided into three regions: Alternative Storage (red circles), Utilized Storage (green circles), and Unutilized Storage (yellow circles). Data points are labeled with storage capacity (Mt) and Pinch values. The y-axis ranges from 0 to 10 Mt/yr, and the x-axis ranges from 0 to 30. A vertical line at Pinch = 20 separates the Alternative and Utilized Storage regions. A horizontal line at Load CO₂ = 5 Mt/yr separates the Utilized and Unutilized Storage regions. The Unutilized Storage region is further divided into two sub-regions by a diagonal line.

Storage Type	Storage Capacity (Mt)	Pinch	Load CO ₂ (Mt/yr)
Alternative Storage	225	0	0
	125	0	2.5
	100	0	5
Utilized Storage	75	15	0
	25	25	2.5
	100	25	5
	25	30	2.5
	25	35	2.5
	200	35	5
	25	40	2.5
	25	45	2.5
	25	50	2.5
	25	55	2.5
Unutilized Storage	400	55	5
	25	60	2.5
	25	65	2.5
	25	70	2.5
	25	75	2.5
	25	80	2.5
	25	85	2.5
	25	90	2.5
	25	95	2.5
	25	100	2.5

Figure 1 is a line graph showing the relationship between CO₂ emissions (Bolan CO₂, Mt) on the x-axis and Water (G) on the y-axis. The x-axis ranges from 0 to 2600 Mt, and the y-axis ranges from 0 to 90 G. Three lines are plotted: a green line for 'Capturable (950 Mt)' at 85 G, a blue line for 'Alternative storage (450 Mt)' starting at 0 G and increasing to 70 G at 1400 Mt, and an orange line for 'Unutilized storage (1250 Mt)' starting at 0 G and increasing to 85 G at 2600 Mt. A red arrow labeled 'Pinch' points to the intersection of the blue and orange lines at approximately (650 Mt, 20 G).

Table 5. Cascade analysis for source and sink with difference time of 10 years.

t (year)	Source, $S_{i,t}$ (Mt/yr)			Sink, $D_{i,t}$ (Mt/yr)	Δt	Flowrate CO_2 (Mt/yr)	Load CO_2 (Mt)	CO_2 cascade (Mt)	
	SR1	SR2	SR3					Infeasible	Feasible
0								0	600
20	15	5	5		20	-25	-500	-500	100
30	20			SK1	10	-10	-100	-600	0
40		10			10	5	50	-550	50
65				SK2	25	35	875	325	925
70					5	15	75	400	1000
80					10	25	250	650	1250
95					15	10	150	800	1400

In the next time difference variable that is pinch point with 10 year time difference. In this cascade table for the 10 year difference show the pinch in the 20-30 year. The cascade table also show the alternative storage of 600 Mt and unutilized storage of 1400 Mt. The captured CO₂ of 800 Mt presents that 36.4% of the 2200 Mt that can be stored in the 3 sinks. The pairing obtained sink 1 as shown in figure 8 receives CO₂ only from source 4 in the 10 to 30 year timeframe and sink 2 receives CO₂ only from source 5 in the 20 to 60 year timeframe. The grid diagram obtained the number of alternative and unutilized storage is suitable with the cascade analysis calculations so that the pairing done with this grid diagram and resulted the exact pairing.

t (year)	Source, $S_{i,t}$ (Mt/y)			Sink, $D_{j,t}$ (Mt/y)	At	Flowrate CO_2 (Mt/y)	Load CO_2 (Mt)	CO_2 cascade (Mt)	
	SR1	SR2	SR3					Infeasible	Feasible
0								0	450
15	15	5	5		15	-25	-375	-375	75
20				SK1 20	5	-5	-25	-400	50
25					5	-10	-50	-450	0
30				SK2 15	5	5	25	-425	25
35					5	5	25	-400	50
40				SK3 10	5	15	75	-325	125
60					20	35	700	375	825
70					10	15	150	525	975
75					5	25	125	650	1100
90					15	10	150	800	1250

In the last time difference variable that is pinch point with 15 year time difference. In this cascade table for the 15 year difference show the pinch in the 20-35 year. The cascade table also shows the alternative storage of 750 Mt and unutilized storage of 1550 Mt. The captured CO₂ of 650 Mt presents that 29.5% of the 2,200 Mt that can be stored in the 3 sinks. The pairing obtained sink 1 as shown in figure 9 receives CO₂ only from source 4 in the 10 to 25 year timeframe and sink 2 receives CO₂ only

from source 5 in the 20 to 55 year timeframe. The grid diagram obtained the number of alternative and unutilized storage is suitable with the cascade analysis calculations so that the pairing done with this grid diagram and resulted the exact pairing.

Fig. 8. CCS grid diagram with 10 year Pinch time difference

Table 6. Cascade analysis for source and sink with difference time of 15 years

t (year)	Source, $S_{i,t}$ (Mt/y)			Sink, $D_{j,t}$ (Mt/y)	Δt	Flowrate CO_2 (Mt/y)	Load CO_2 (Mt)	CO_2 cascade (Mt)	
	SR1	SR2	SR3					Infeasible	Feasible
0	SR1	SR2	SR3					0	750
15					20	-25	-500		
20	SR4							-500	250
25				SK1	5	-30	-150		
30					5	-10	-50	-650	100
35					5	-10	-50	-700	50
40					5	-10	-50	-750	0
45					5	5	25	(PINCH)	25
50					5	25	125	-725	
55					5	25	125	-600	150
60					5	35	875		
65					5	35	875	275	1025
70					15	25	375		
75					15	25	375	650	1400
80					15	10	150	800	1550

Fig. 9. CCS grid diagram with 15 year Pinch time difference

From some of the above variables, it can be concluded that the best pairing occurs when the time difference variable is 0 years. It can be seen from the percentage of carbon captured with dt 0 that is 50% larger than using other dt as in the table shown in table 7.

Table 7. Results calculation of CSS with pinch diagram and cascade analysis

Δy (year)	Alternative storage (Mt)	Carbon Capturable (Mt)	Unutilized storage (Mt)	% CC
0	300	1100	1100	50
5	450	950	1250	43.2
10	600	800	1400	36.4
15	750	650	1550	29.5

4 Conclusion

The result from each grid diagram obtained shows the exact pairing based on the suitability of alternative and unutilized storage with composite curve and table cascade calculations. The result shows that the larger time difference the larger alternative storage and unutilized storage capacities. Therefore, having a shorter time difference will be more acceptable in the design CCS system.

The author would like to express his gratitude for the financial support from Kemenristekdikti under the contract no 582/PKS/ITS/2017

References

1. IPCC, *IPCC Special Report on Carbon Dioxide Capture and Storage Intergovernmental Panel on Climate Change* (Cambridge University Press, New York, 2005)
2. J. A. R. Diamante, R. R. Tan, K. B. Aviso, S. Bandyopadhyay, D. K. S. Ng, D. Y. Foo, *Proceedings of the 6th International Conference on Process Systems Engineering, PSE ASIA*, (2013)
3. M. M. El-Halwagi, V, *A.I.Ch.E. J* **35**, 1233-1244 (1989)
4. R. E. H. Ooi, D. C. Y. Foo, D. K. S. Ng, R. R. Tan, *Che. Eng. Rsch. and Dsgn.*, **91**, 2721-2731 (2013)
5. R. Smith, *Chemical Process Design and Integration* (John Wiley & Sons, England, 2005)