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Regional and Total Site CO_2 Integration Considering Purification and Pressure Drop

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The application of Pinch Analysis (PA) targeting method has been recently explored to the design of CO_2 emission reduction in Total Site planning of CO_2 capture, utilisation and storage. The algebraic method based on Problem Table Algorithm (PTA) for Total Site CO_2 Integration (TSCI) provides the designer with integrated CO_2 capture, utilisation and storage (CCUS) for the optimal CO_2 emission reduction. In TSCI, CO_2 is captured with certain quality from various plants and supply into system header pipeline. The CO_2 header could satisfy various CO_2 demands for various industry located in the header, and only surplus CO_2 is to be sent to storage. The extended methodology with consideration of purification and pressure drop in TSCI planning is proposed. The CO_2 supply from the header could satisfy the purity demand through a process of purification. Purification is a process to upgrade the purity level have not been considered in the previously used in TSCI method. In addition, pressure drop during CO_2 transportation in the pipeline system has been included to identify the implication of pressure drop in TSCI design and has resulted about 29.01 MPa of the total pressure drop (ΔP_d). Therefore, 68.2 t/h of flow rate (F_T) of 81 % purity level header is supplied and purified to satisfy the 50 t/h of demand, at 99 % purity level. The improved methodology of TSCI network has been further developed and provides a more realistic scenario for CCUS implementation.

1. Introduction

CO_2 capture, utilisation or sequestration has received considerable attention as a logical pathway to mitigate global warming effects. In year 2014, the concentration of CO_2 (397 ppm) was about 40 % higher than the mid-1800s (IEA 2015). Energy-intensive industrial production is responsible for about 60 % of the total anthropogenic CO_2 emissions, which include power plants, cement production, refineries, iron and steel industries, gas processing and petrochemicals (Čuček et al., 2015). Cost and further energy demand are the current major barrier for CO_2 capture, sequestration or storage (CCS) (Rubin et al. 2013) included CO_2 transfer from sources to dedicated storage. CCS project in Southeast United State (505 km-pipe length; 24 in-diameter) and Wyoming (373 km-pipe length; 20 in-diameter), CO_2 pipeline transportation capital cost for these two locations is estimated about 370 M$ to 740 M$ for 42,320 t CO_2/d capacity and 135 M$ to 430 M$ for 38,280 t CO_2/d capacity (NETL 2013). Consequently planning and long-term strategies are needed to cluster the CO_2 sources and develop CO_2 pipeline networks (Jensen et al. 2013) such as source-to-sink transmission of CO_2 at an optimal operation.
PA or source-sink matching method has been developed from Heat Integration (Klemeš, 2013), extension to Total Site Heat Integration (Klemeš et al., 1977) and explored for CCS planning development (Klemeš et al., 2013). Ooi et al. (2013) introduced a planning method for CCS using PA. A graphical targeting tool is proposed to plan the CO_2 captured from the power plants into CO_2 storage facilities. To minimise the need to transport CO_2 over long distances from the sources to storage, Diamante et al. (2014) highlighted the injectivity constraint of sinks and time availability of potential sources and sinks using graphical and algebraic

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approaches. Zhang et al. (2015) extended the Process Integration methods for optimal operation characteristics in the CCS system by targeting Pinch Temperature to integrate heat pumps and refrigerator for waste heat recovery. Krishna Priya and Bandyopadhyay (2015) have introduced a PA based approach for the viability of capture technology using the concept of prioritised cost for retrofitting into existing power plants. Kim et al. (2015) made an attempt to introduce GHG Footprint Composite Curves and Giaouriset al. (2015) extended Power Grand Composite Curves approach introduced by Wan Alwi et al. (2012) into adaptive operation of renewable energy smart grids. Total Site CO_2 Integration (TSCI) planning tool is introduced (Mohd Nawi et al. 2015) to maximise the CO_2 exchange between CO_2 sources and demands using central pipeline header before sending the excess CO_2 to storage. The main challenge in TSCI is the cost to integrate the sources, demands and storage and CO_2 transfer across distance. Besides pipeline distance, other major components for cost estimation are compressor power and additional CO_2 purifier. An extended TSCI with consideration of purification and pressure drop during CO_2 transfers is proposed in this study. Purification processes is used to upgrade the concentration to satisfy a high purity CO_2 demand and have been widely used in the hydrogen network (Wang et al. 2016) to reduce production load. Pressure drop is highlighted to ensure that process transfer of CO_2 in the pipeline is function normally and an unanticipated pressure drop may resulted in leakage (Noothout et al. 2013). This extended methodology with consideration of these two important parameters in CO_2 transportation via pipeline would give a realistic scenario for TSCI implementation.

2. Methodology with illustrated case study

There are currently about 6,500 km of CO_2 pipeline worldwide, which most of them are linked to EOR operations that associated with or under development for CO_2 storage (Noothout et al. 2013). Dense phase or supercritical condition for CO_2 is the most efficient way to transport via pipeline and it is required to maintain the pressure in the pipeline above the critical point of CO_2 (Wetenhall et al. 2014). In the Gas Processors Suppliers Association (GPSA) Engineering Data book (GPSA 1998), the critical point of CO_2 occurs at a pressure of 7.38 MPa and a temperature of 31.4 °C and most widely used operating pressure is between 7.4 and about 21 MPa to ensure CO_2 single-phase flow in the pipeline (Dakota Gasification Company 2016). High inlet pressure or booster stations installation at every 100 km to 150 km are required to make up the pressure losses (Wong 2013) as pressure drop increases with the increasing of flow rate (Seevam et al. 2010). In this study, single phase or supercritical CO_2 is assumed in the pipeline system transportation. The critical point properties of CO_2 are at 31 °C and 7.37 MPa and density of CO_2 at this point is assumed 467.69 kg/m^3 (Fenghour et al. 1998).

2.1 Identify CO_2 sources and demands

Eight sources of potential CO_2 captured points and four potential of CO_2 demands in a potential area (Mohd Nawi et al. 2016) have been identified for an integrated network. The developed methodology had targeted the CO_2 purity at each point of header to optimal CO_2 utilisation, minimum fresh CO_2 supply needed and a minimum of CO_2 sent to storage. Tables 1 and 2 show the CO_2 sources and CO_2 demands and their corresponding data.

Table 1: Data for CO_2 sources

Source	Description	F_T (t/h)	P_{CO2}	Distance (km)	F_{CO2} (t/h)	F_{OG} (t/h)
S1	Cement	138.8	0.90	410	124.9	13.9
S2	Refineries/ chemical	608.5	0.70	390	425.9	182.5
S3	Power (coal based)	1,174.3	0.85	360	998.2	176.1
S4	Power (NG based)	101.5	0.88	290	89.3	12.2
S5	Agricultural	69.9	0.65	270	45.4	24.4
S6	rochemical	615.4	0.80	210	492.3	123.1
S7	Gas processing	36.5	0.90	190	32.8	3.6
S8	Iron & steel	27.9	0.95	150	26.5	1.4

Table 2: Data for CO_2 demands

Demands	Description	F_T (t/h)	P_{CO2}	Distance (km)	F_{CO2} (t/h)	F_{OG} (t/h)
D1	Beverage plant	50.0	0.99	340	49.5	0.5
D2	Enhance oil recovery	208.3	0.80	240	166.6	41.7
D3	Methanol production	83.3	0.50	110	41.7	41.7
D4	Micro algae production	220.0	0.10	100	22.0	198.0

F_T is the total flow rate of flue gas and P_{CO2} is the purity of CO_2 in the total flue gas which gives the value of CO_2 flow rate (F_{CO2}) and other gases flow rate (F_{OG}). Beside CO_2 has been also other gases some of them strong GHG - (F_{OG}) such as N_2, CO, NOx, SOx and N_2 included in the flue gas. Distance (km) is estimated from the point of sources or demands through a header to the storage.

2.2 CO_2 Total Site – Problem Table Algorithm

The CO_2 sources and demands are matched by targeting the maximum CO_2 utilisation before the remaining capture CO_2 is sent to storage. Noted that one header is constructed in this study and Figure 1 illustrates the TSCI network. The step by step construction of CO_2 Total Site Problem Table Algorithm (CTS-PTA) methodology is described by Mohd Nawi et al. (2016). The sources and demands are arranged based on their location along the header (Column 1). F_T is extracted in Column 2 followed by P_{CO2} and F_{CO2} in Columns 3 and 4. The positive value of flow rate represents sources and negative is for demands. Next step is to match the sources and demands. Cumulative F_T in Column 5 and F_{CO2} in Column 6 are cascading downwards and cumulative P_{CO2} (Column 7) is indicated by dividing the cumulative F_{CO2} with F_T cumulative as shown in Table 3. In order to match CO_2 sources and demand, the F_T header would be directly supplied to the demands if the required demand purity is lower or equal to the header purity. However, if the demand requires higher purity than the header purity, a purification process is proposed to satisfy the demand.

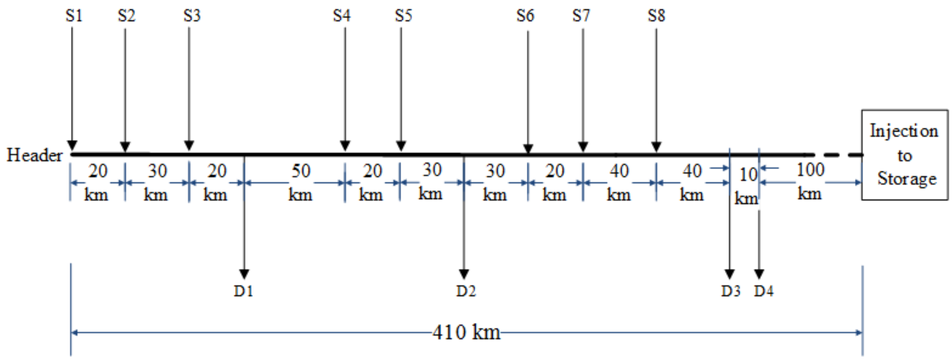

Figure 1: CO_2 sources (S) and demands (D) through a header

2.3 Calculate purification process

For a demand that requires a higher purity than the CO_2 purity in the header, a purifier is considered to utilise CO_2 from header to demand site. The purification process generates two outputs (Zhang et al. 2011) – one of which with higher purity as the product, F_{Di} and the other one is by product or tail gas (F_{Gi}). The cumulative flow rate from the header to satisfy D1, $F_{in,(H-Di)}$ is calculated by using Eq(1) as stated in Column 5. Eq(2) is used to calculate the tail gas flow rate (F_{Gi}) of the process and Eq(3) to determine the purity of the tail gas of the system.

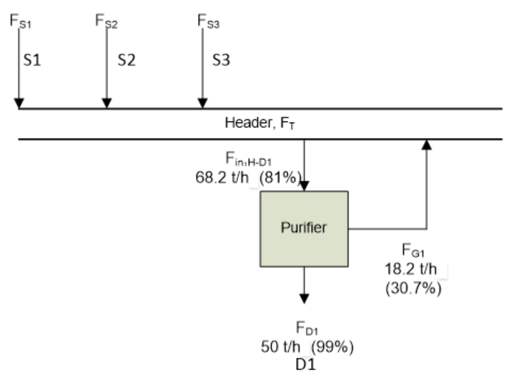

Figure 2: Mass balance for purification process

The tail gas is supplied back into the header and purity of F_{Gi} is indicated as P_{Gi}. Figure 2 illustrates this arrangement. The recovery efficiency (R) of the purification process is assumed 0.9.

$$F_{in,H-Di} = \frac{F_{T,Di} \; x \; P_{CO2,Di}}{R(P_{CO2,H})} \quad (1)$$

$$F_{Gi} = \; F_{in,H-Di} - F_{Di} \quad (2)$$

$$F_{inH-Di}P_{H-Di} = F_{Di}P_{Di} + \; F_{Gi}\,P_{Gi} \quad (3)$$

For a demand that requires equal or lower purity (P_{CO2}) than CO_2 purity (P_H) in the header, $F_{in,(H-Di)}$ is directly supplied per demand required without purifier installation as stated in TSCI purity rule concept (Mohd Nawi et al. 2016). Eq(4) and Eq(5) represent the direct supply of flow rate from header to demand.

$$F_{in,H-Di} = F_{Di} \quad (4)$$

$$F_{inH-Di}P_{H-Di} = F_{Di}P_{Di} \quad (5)$$

2.4 Calculate pressure drop

Pressure drop due to friction along CO_2 pipeline transportation is calculated as pressure is the most important to ensure that CO_2 transportation function normally. Eq(6) is pressure drop estimation (Fox and McDonald 1992), where f is the friction factor (0.0165), m is mass flow rate (kg/s), ρ is the fluid density (kg/m^3), L is pipe length (km) and D is pipe diameter (m). For turbulent pipe flow that typically fluids flow in a plant, f depends on the Reynolds number and relative roughness $\mathcal{E}/D$, ratio of a mean height of roughness of the pipe to the pipe diameter. The value is following the Colebrook equation, Eq(7) and has been simplified into Moody chart to present Darcy friction factor for circular pipe flow (Cengel and Cimbala 2006). A roughness value ($\mathcal{E}$) of 0.0457 mm has been used as the recommended value for commercial steel pipelines (Wetenhall et al. 2014) and diameter of the pipe is assumed to be 27-in (Noothout et al. 2013) to estimate the pressure drop in this study. Note that L (km) in Column 11 is the pipe length between each of source or demand points.

$$\Delta P_d = f\,\frac{m^2}{\rho}\,\frac{L}{D^5}\,\frac{8{,}000}{\Pi^2} \quad (6)$$

$$\frac{1}{\sqrt{f}} = \; -1.8\log\left[\frac{6.9}{Re} + \left(\frac{\mathcal{E}/D}{3.7}\right)^{1.11}\right] \quad (7)$$

The CTS-PTA with purifier installation and estimation of pressure drop due TSCI network is given in Table 3. The last row in Cum F_T and Cum F_{CO2} gives the minimum target to be sent to CO_2 storage for permanently stored. Total pressure drop is 29.01 MPa as shown in the last row of Column 14 (Cum ΔPd). Three points of compression are considered in the TSCI design network to transport CO_2 along the header as shown in Figure 3. Each of the compression points is assumed to make up about 10 MPa of pressure losses along the header and 0.085 MW capacity of each compressor is required, based on 8.5 kWh/t of energy consumption is required for 1 MPa CO_2 compression (Wong, 2013).

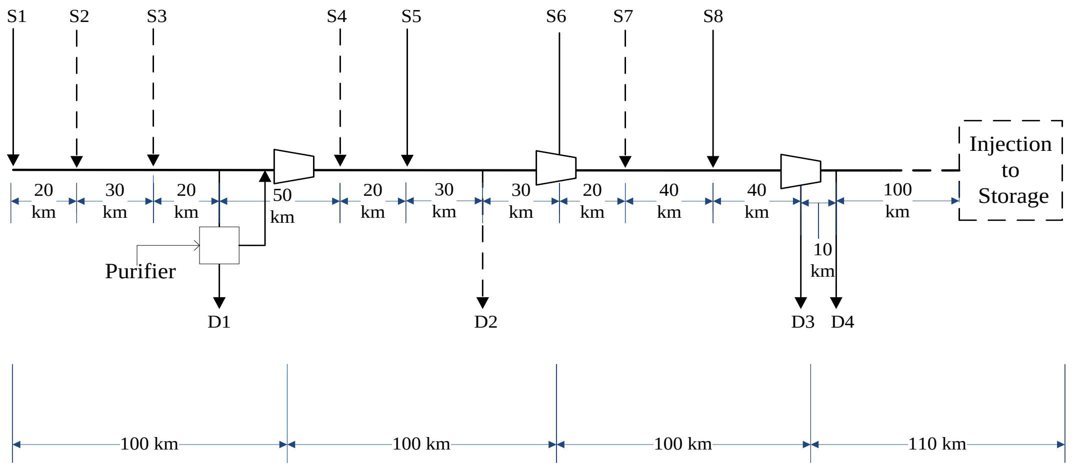

Figure 3: TSCI design with purifier and compressors

3. Conclusion

TSCI has a potential to integrate major CO_2 emitter supplies into a centralised system and able to supply to any potential demands along the header. This paper is an improved TSCI methodology for further development in CCUS planning. A unit of purification is identified to satisfy the demand that requires higher CO_2 purity than the header. The total pressure drop (ΔPd) of TSCI network in this study is 29.01 MPa at the range of 410 km of pipeline length. The improved TSCI methodology with consideration of purification process and compression is seen as realistic assessment for CCUS development. Further works can include cost tariff analysis of TSCI to estimate the cost of sequestration for each plant that wants to supply their CO_2 into centralised header system.

Table 3: The CTS-PTA and pressure drop calculation

	1	5	6	7	8	9	10	11	12	13	14
i	**S/D**	**Cum F_T**	**Cum F_{CO2}**	**Cum P_{CO2}**	**$F_{in, (H-D)}$**	**F_G**	**P_G**	**L (km)**	**Cum F_T or m (kg/s)**	**ΔPd (MPa)**	**Cum ΔPd (MPa)**
1	S1										
		138.79	124.91	0.90				20	38.55	0.01	
2	S2										0.01
		747.29	550.86	0.74				30	207.58	0.22	
3	S3										0.23
		1,921.59	1,549.02	0.81				20	533.78	0.97	
4	D1				68.23	18.23	0.30				1.20
		1,853.36	1,494.02	0.81				50	514.82	2.26	
5	S4										3.45
		1,954.86	1,583.34	0.81				20	543.02	1.00	
6	S5										4.46
		2,024.76	1,628.77	0.80				30	562.43	1.62	
7	D2				208.30	-	-				6.07
		2,233.06	1,796.33	0.80				30	620.29	1.97	
8	S6										8.04
		2,848.41	2,288.61	0.80				20	791.23	2.13	
9	S7										10.17
		2,884.87	2,321.43	0.80				40	801.35	4.38	
10	S8										14.55
		2,912.77	2,347.93	0.81				40	809.10	4.46	
11	D3				83.30	-	-				19.01
		2,829.47	2,280.79	0.81				10	785.96	1.05	
12	D4				220.00	-	-				20.06
		2,609.47	2,103.45	0.81				100	724.85	8.95	
											29.01

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