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Effects of Impurities on CO_2 Pipeline Performance

Suoton P. Peletiri, Nejat Rahmanian*,Iqbal M. Mujtaba

Chemical Engineering Program, School of Engineering, University of Bradford, Bradford. BD7 1DP, UK
n.rahmanian@bradford.ac.uk

Carbon dioxide (CO_2) is a chief constituent of greenhouse gases and should be captured, transported and stored in saline aquifers or used for enhanced oil recovery. This study is focused on pipeline transportation of impure CO_2. The major impurities in captured CO_2 from power plant stations and gas processing facilities are mainly nitrogen, methane, hydrogen sulphide, and water. Impurities affect the density and viscosity of the CO_2 stream thereby impacting on the fluid phase, pressure and temperature of the stream. CO_2 pipeline models, however, rarely consider the effects of impurities in the determination of design parameters. Aspen HYSYS (ver.9) is used to model the effect of impurities on the pressure drop, phase envelope and critical pressure and temperature of captured CO_2 fluids flowing in pipelines. Cortez, Canyon Reef and Choctaw pipelines in the USA and Weyburn pipeline in Canada were selected as the case studies. The results show that the pressure drop increased in these pipelines due to the impurities with the highest pressure drop occurring in the Canyon Reef pipeline. The impurities increased the pressure drop by about 0.09 bar/km, 0.2 bar/km, 0.10 bar/km and 0.04 bar/km for Cortez, Canyon Reef, Choctaw and Weyburn pipelines respectively. The lower molecular weight gases were found to decrease the mixture density and increase the pressure drop. The results also reveal that the bubble point pressure was increased by impurities in three pipelines but slightly reduced in the Weyburn pipeline and the critical temperature was reduced in all pipelines.

Keywords: Impure CO_2, phase envelope, CO_2 transportation, pressure drop.

1. Introduction

As the emission of greenhouse gases rises, the need for global warming mitigation efforts are expected to increase. This need was brought to the fore once again in the recent Paris agreement which entered into force on 4 November 2016 where 193 signatories signed onto the agreement (United Nations, 2015). It is hoped that most of these countries would take practical steps in capturing CO_2 and transporting it to storage sites or for enhanced oil recovery (EOR) operations or other uses. Up to 360,000 km of pipelines may be required to transport the CO_2 captured from industrial processes by 2050 (IEA GHG, 2014). The United States, the leading country in CO_2 pipeline infrastructure, is projected to construct additional CO_2 pipelines of between 17,700 and 37,000 km before 2050 (Dooley et al., 2009). Therefore, more pipelines would be constructed to transport the increased volume of CO_2 captured from large point sources (Mazzoldi et al., 2008). There were just over 6,500 km of CO_2 pipelines worldwide with most transporting CO_2 for enhanced oil recovery in the United States (Dooley et al., 2009, Noothout et al., 2014, IEA GHG, 2014).
CO_2 is transported in pipelines above the supercritical pressure of 73.8 bar and temperature of 31.1 ^oC to keep it in supercritical state. Some researchers reported pipeline operating pressures and temperatures to range from 86.2 to 151.7 bar (Forbes et al., 2008), 100 to 150 bar and 15 to 30 ^oC (Patchigolla and Oakey, 2013) and 85 to 150 bar and 13 to 44 ^oC (Kang et al., 2014).
CO_2 pipeline streams are usually impure and may contain several impurities. Porter et al. (2016) classified CO_2 stream impurities into three main categories arising from fuel oxidation, excess oxidation/air ingress and process fluids. These impurities affect both the physical and thermodynamic behaviour of the CO_2 fluid. Table 1 shows CO_2 captured from both natural and industrial sources. The type and percentage of the impurities depend on the source (naturally occurring or fuel type) and type of capture (pre-combustion, oxy-fuel or post-combustion). CO_2 pipeline streams may contain nitrogen, methane, hydrogen sulphide, carbon monoxide,

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nitrogen oxide, oxygen, sulphur oxide, hydrogen, water, etc. (Li et al., 2011), these impurities may arise from combustion products, fuel type, air ingress, CO_2 capture materials and chemicals (Porter et al., 2015).

Table 1: CO_2 pipelines with impurities in mol % (Patchigolla and Oakey, 2013).

	Canyon Reef Carriers	Central Basin Pipeline	Sheep Mountain	Cortez Pipeline	Weyburn
CO_2	85 – 98	98.5	96.8 – 97.4	95	96
CH_4	2 -15	2 – 15	1.7	1 – 5	0.7
N_2	< 0.5	< 0.5	0.6 – 0.9	4	< 0.03
H_2S	< 0.02	< 0.02 wt		0.002	0.9
C_2+			0.3 – 0.6	Trace	2.3
CO					0.1
O_2		< 0.001 wt			< 0.005wt
H_2					Trace
H_2O	0.005 wt	0.0257 wt	0.0129 wt	0.0257 wt	0.002 v

To effectively design a CO_2 pipeline, several factors are taken into consideration, including flow assurance, pipeline integrity, pipeline operations and health and safety (Lazic et al., 2014). The physical properties, density and viscosity, of the flowing fluid are either direct or indirect input parameters into the pressure calculation equation of CO_2 pipelines and must be determined correctly. Density of CO_2 increases if the pressure increases or temperature decreases, while the viscosity increases with increase in pressure (Yener et al., 1998) and increase in temperature.
Since CO_2 is transported in the supercritical phase in pipelines, the critical pressure and temperature need to be determined. The change in the critical pressure and temperature may not be significant due to the high content of CO_2. However, for design purposes, the pressures and temperatures that will cause a change in phase, temperature and pressure variations has to be known. The Peng-Robinson EOS, which had the least absolute average deviation (AAD) among the cubic EOS for predicting density of binary CO_2 mixtures (Mazzoccolia et al. 2013) and the best in calculating critical temperature and pressure of CO_2 (Zhao and Li, 2014), was used in Aspen HYSYS (ver.9).

The following assumptions were made:

- Pipelines are horizontal though recognising that the pipelines considered may not be horizontal for the entire length.
- The input (maximum) pressure for all pipelines is 150 bar.
- Minimum operating pressure is 100 bar.

2. Critical points

CO_2 pipelines operate above the critical pressure and temperature to keep the fluid in a single phase during transportation. It is therefore imperative to know the critical pressure and temperature of the streams in pipeline fluids for effective operation. All impurities increase the critical pressure and only SO_2 and H_2S increase the critical temperature while all others reduce the critical temperature. An increase in critical pressure requires more energy for compression of the fluid to supercritical state. Table 2 lists the critical pressure and critical temperature of a stream of 10 % impurity in 90 % CO_2. Table 3 shows the critical pressure and temperature of pure CO_2 and the four pipelines.

Table 2: critical pressure and critical temperature of pure components.

Components	CO_2	CH_4	N_2	H_2S	O_2	SO_2	CO	NO	H_2
Critical pressure (bar)	73.7	79.39	88.15	74.53	86.44	85.11	87.83	89.1	107.7
Critical temperature (^oC)	30.95	23.25	23.61	33.29	24.41	49.84	23.48	24.83	28.34

Table 3: critical pressure and critical temperature of pipelines

Pipelines	CO_2	Cortez	Weyburn	Choctaw	Canyon Reef
Critical pressure (bar)	73.7	78.88	73.38	79.51	80.30
Critical temperature (^oC)	30.95	27.57	29.17	26.51	22.46

3. Pressure drop

Rich CO_2 pipelines are usually in the dense phase with pressures above the critical pressure value, without discontinuities in the fluid properties when the temperature drops below the critical value (Raimondi 2014). In CO_2 pipeline design, CO_2 flow rate is ascertained and pipeline pressure drop and optimal pipeline diameter are calculated. Several researchers have proposed different forms of similar equations for the determination of pipeline diameter and/or pipeline pressure drop. The one given in IEA GHG (2002) is presented in Eq(1).

$$\Delta P = 2.252 \frac{f L \rho Q^2}{D_i^5} \tag{1}$$

where ΔP = pressure drop (bar), f = friction factor, L = pipeline length (km), ρ = fluid density (kg/m^3), Q = flow rate (l/m) and D_i = pipeline inner diameter (mm).
The equation presented by Chandel et al.,(2010) incorporating elevation changes is given in Eq(2).

$$\Delta P = \frac{f \rho l u^2}{2 D_i} + \rho g \Delta z \tag{2}$$

where ΔP is pressure drop (MPa), f is friction factor, l is the length (m), u is velocity (m/s), D_i is the pipeline internal diameter (m), ρ is the fluid density (kg/m^3), g is acceleration due to gravity (m/s^2) and Δz is change in elevation (m).
Both density, ρ and friction factor, f are functions of fluid composition and the amount of impurities in the stream affect both of these parameters. Impurities in CO_2 pipelines may range from 0.1 % to above 10 %. Kaufmann (2011) stated that as long as the impurities concentration is not much greater than 2.5 %, the critical pressure increase also remains below 5 %. This marginal increase in critical pressure is important for design purposes and most pipelines contain more than 2.5 % impurities. Most impurities cause an increase in the critical pressure and pressure drop in CO_2 pipelines. This is of great concern as it increases both the capital cost and operations and maintenance (O&M) cost of CO_2 pipelines. Hydrogen (H_2) when present causes the most pressure drop and sulphur dioxide (SO_2) has the highest reduction of pressure loss.

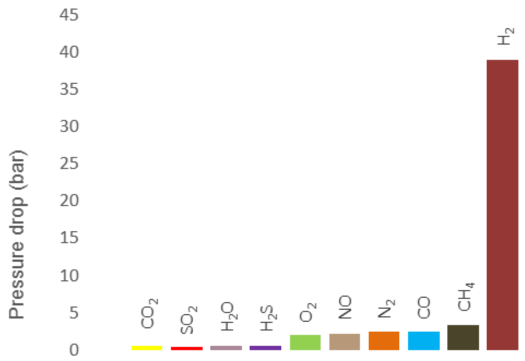

Figure 1: Relative pressure drop due to pure components

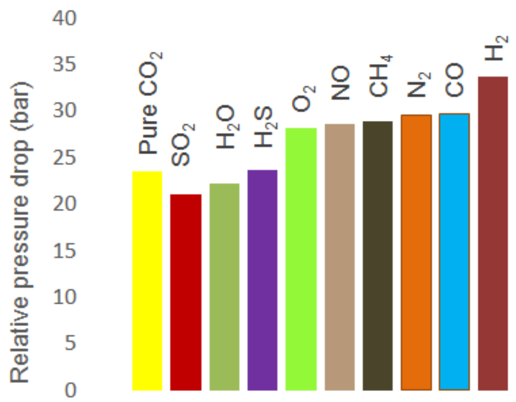

Figure 2: Relative pressure drop of 10% single impurity in Co_2 fluid

Figure 1 shows the pressure drop of pure impurities in a 70 km, 457.2 mm diameter pipeline with a flow rate of 100 kg/s and input pressure of 150 bar. The pressure losses of a pure hydrogen pipeline is 87.5 times that of pure CO_2 and SO_2 has only 0.66 times that due to pure CO_2. Figure 2 shows a comparison of 10 mol % single impurity and 90 mol % CO_2 stream. Though the presence of water is undesirable because it may cause pipeline corrosion, two-phase flow or block the pipeline due to hydrate formation (Chapoy et al., 2013), it reduces the pressure loss. Single components in a similar pipeline showed the following pressure drops in comparison to pure CO_2. SO_2 – 65 %, H_2O – 94 %, H_2S - 112 %, O_2 – 396 %, NO – 451 %, N_2 – 489 %, CO – 490 %, CH_4 - 734 % and H_2 – 8039 %; see Figure 1. For 10 % single impurity, the binary component fluids showed the following percentages of pressure drop relative to pure CO_2. SO_2 – 89.5 %, H_2O – 94.3 %. H_2S – 100.3 %, O_2 –119.3 %, NO – 121.4 %, CH_4 – 122.4 %, CO – 125.8 %, N_2 – 125.5 % and H_2 – 142.7 %; see Figure 2.

4. Phase envelopes

Though CO_2 pipelines are defined as pipelines with 90 % or more of CO_2 at supercritical pressures, there are some advantages of transporting liquid CO_2 over supercritical CO_2 including increased volume transported due to increased density and reduced pressure losses (Zhang et al., 2006). CO_2 fluids enter the liquid phase if the temperature drops below the critical temperature when pressures are above the critical pressure. All pipelines considered here show reduced critical temperatures. Figure 3 shows the phase diagrams of the four pipelines.

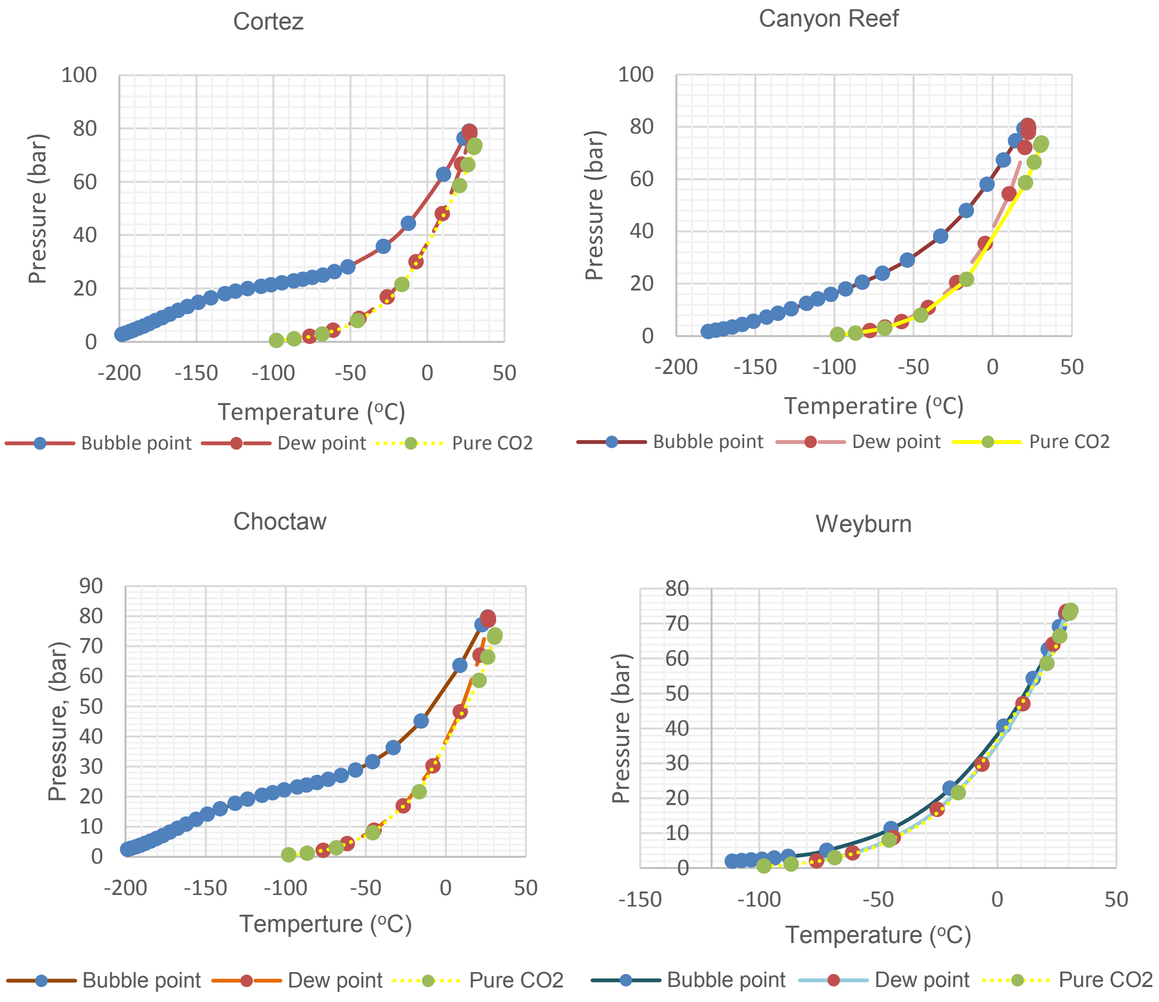

Figure 3: Phase envelopes of Cortez, Canyon Reef, Choctaw and Weyburn pipeline fluids.

The dew point curves of all pipelines closely matched the liquid – vapour line of pure CO_2. The two – phase region widens as the percentage of impurities and fraction of lighter gases increase. The P – T diagram of the Weyburn pipeline closely matched that of pure CO_2 because it has the least percentage of impurities and a fairly high fraction of C_{2+} which is not in other pipelines. The wider the bubble and dew point curves, the easier the fluid enters the two – phase region during transportation due to a reduction in temperature and/or pressure. The pressure drop due to impurities under the above assumptions, increased the number of booster stations from four to five for Cortez, 2 to 3 for Canyon Reef, but no change at two each for Choctaw and Weyburn pipelines.

5. Conclusions

For optimum operation of CO_2 pipelines; flow rates, pressures, temperatures and impurities in the stream must be adequately known. These factors are then used in the design and operation of the pipelines. The effect of impurities on the phase envelope, pressure drop and critical pressure and temperature has been studied and the following conclusions are reached.

- No impurity is desirable because they create a two-phase region.
- The lighter components than CO_2 cause an increase in pressure losses.
- The relative pressure drop due to impurities in the pipelines range from 4 % to 20 %
    a. Cortez pipeline – 9.03 %
    b. Canyon Reef – 20.25 %
    c. Choctaw – 10.25 %
    d. Weyburn – 4.02 %
- H_2, though not present in any of the pipelines considered, when present causes the highest increase in pressure drop followed by CO, N_2, CH_4. NO, O_2 and H_2S while H_2O and SO_2 cause a decrease in pressure loss.
- All common impurities increase the critical pressure of the CO_2 fluid. Only the Weyburn pipeline showed a reduction in critical pressure and this may be due to the presence of C_{2+} represented by C_2H_6. An increase in critical pressure requires higher operating pressures and consequently stronger or thicker pipes and higher energy requirements for compression to keep the fluid in the supercritical state.
- All pipelines showed critical temperatures lower than the critical temperature of pure CO_2. However, when pressures are above the critical pressure, the temperature is not a serious consideration unless temperatures drop low enough for solid formation. Above the critical pressure, fluids with higher critical temperatures will entered the liquid phase before fluids with lower critical temperatures.

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