IMPACT OF CO_2 STREAM IMPURITIES ON DUCTILE AND BRITTLE FRACTURES IN CO_2 PIPELINES

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Extended Abstract

As part of the Carbon Capture Utilization and Storage (CCUS) chain, it is widely accepted that pressurised pipelines offer the safest and the most economical way of transporting large quantities of carbon dioxide (CO_2) captured from industrial emission sources and fossil fuel power plants for permanent geological storage or utilisation. However, given that CO_2 is an asphyxiant at connections > 10% v/v[1], in the unlikely event of the failure of such pipelines near a populated area, the potential consequences could be significant.

A recent case in example is the rupture of a 24-inch pressurised CO_2 pipeline in Satartia, Mississippi in Feb 2020, releasing liquid CO_2 that immediately began to vaporize at atmospheric conditions[2]. 45 people required hospitalisation; some having been found unconscious in their cars whilst attempting to escape the engulfing CO_2 plume. The incident, currently under investigation by the US Department of Transport has since resulted in significant public backlash, potentially jeopardizing the chances of CCUS deployment in the US.

The unique thermophysical properties of CO_2, make CO_2 pipelines particularly susceptible to the risk of a small diameter through-wall defect transforming into a propagating fracture resulting in the release of a massive amount of inventory in a very short space of time. Such an event may significantly undermine the effectiveness of emergency response planning including emergency pipeline isolation or public evacuation.

CO_2 pipelines can fail either in ductile, brittle or the combination of the two fracture modes. Figure 1 shows a schematic representation of both types of failure depicting their different propagation characteristics and pipeline deformation.

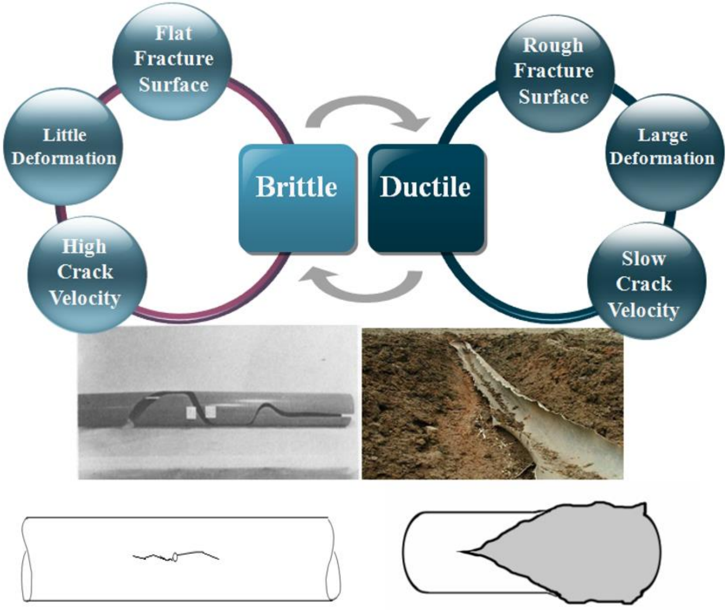

Figure 1. Schematic representations of ductile and brittle pipeline fractures

In the case of ductile fractures, if the fluid decompression wave velocity is larger than the crack velocity, the crack tip stress will decrease, eventually dropping below the arrest stress causing the crack to arrest. Conversely, if the decompression wave velocity remains smaller than the crack velocity, the crack tip pressure will remain constant resulting in indefinite propagation.

Compared to natural gas, CO_2 has an unusually high saturation pressure thus making CO_2 pipelines particularly susceptible to ductile fracture propagation failure[3]. As such accounting for any parameters that may modify the CO_2 depressurisation trajectory is of paramount importance when modelling ductile fractures in CO_2 pipelines. One such important factor is the impact of impurities given that even small amounts will significantly increase the CO_2 saturation pressure[4].

The failure mechanism for the transition of a through-wall defect into a brittle fracture is somewhat different. Here the Joule Thomson expansion cooling of the escaping CO_2 can lead to temperatures as low as -70 °C. If the pipe wall temperature drops below the pipeline material ductile to brittle transition temperature, a significant drop in the pipeline fracture toughness will incur. If, and when the accompanying thermal and pressure stresses during the decompression process exceed the pipeline fracture toughness, a propagating brittle fracture will occur.

This paper investigates the impact of the typical CO_2 impurities associated with different types of capture technologies, covering pre-combustion, post-combustion and oxyfuel on the propensity of CO_2 pipelines in undergoing ductile and brittle fracture propagation failures.

Methodology

The background theory based on a fluid-structure interaction model for simulating ductile and brittle fracture propagation in CO_2 pipelines is published elsewhere [5,6]. Briefly, the transient fluid flow behaviour during decompression is obtained based on the numerical solution of the conservation equations using the Method of Characteristics implemented into the PipeTech[7] pipeline rupture software. The conditions at the rupture plane are determined by carrying out an energy balance across the orifice assuming isentropic expansion. The accompanying 3-D thermal and pressure stresses in the proximity of the defect are obtained using finite element analysis accounting for the initial through-wall defect geometry.

Figures 2 & 3 show the corresponding calculation flow algorithms for ductile and brittle fracture modelling respectively.

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[1] Bilio, M., Brown, S., Fairweather, M. and Mahgerefteh, H., ‘CO2 Pipelines material and safety considerations’, HAZARDS XXI Process Safety and Environmental Protection, Institution of Chemical Engineers (IChemE) Symposium Series No. 155 (2009) 423 – 429.

[2] Failure Investigation Report – Denbury Gulf Coast Pipelines LLC, Pipeline Rupture/Natural Force Damage, Feb 2022 https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2022-05/Failure%20Investigation%20Report%20-%20Denbury%20Gulf%20Coast%20Pipeline.pdf

[3] Mahgerefteh, h., Brown, S. and Zhang, P., ‘A dynamic boundary ductile-fracture-propagation model for CO2 pipelines’, Journal of Pipeline Engineering 9(4) (2011) 265 - 276.

[4] H., Yan, J., 2006. Impact of impurities in CO_2-fluids on CO_2 transport process.:Proceedings of GT2006, Barcelona, pp. 367–375.

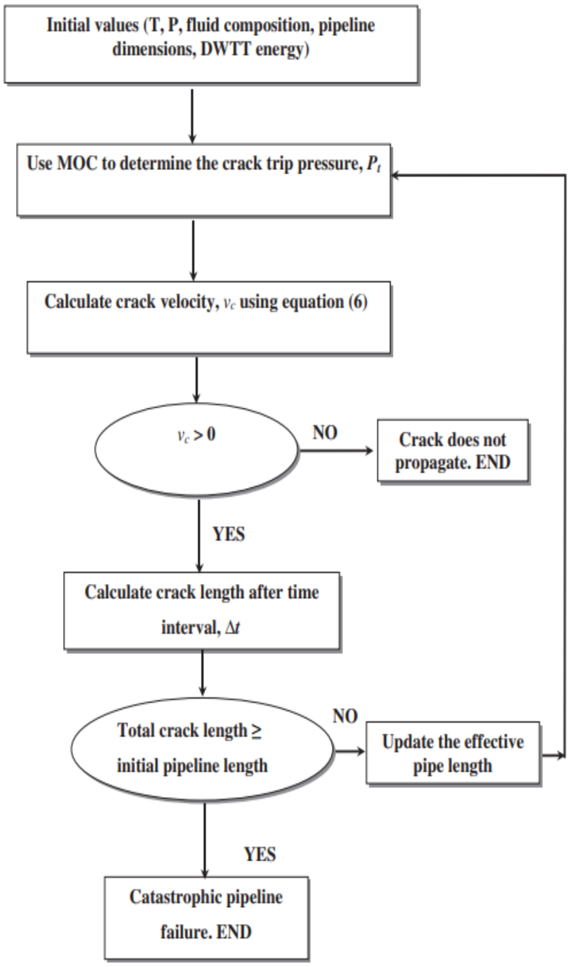


Figure 2. Ductile fracture propagation calculation algorithm

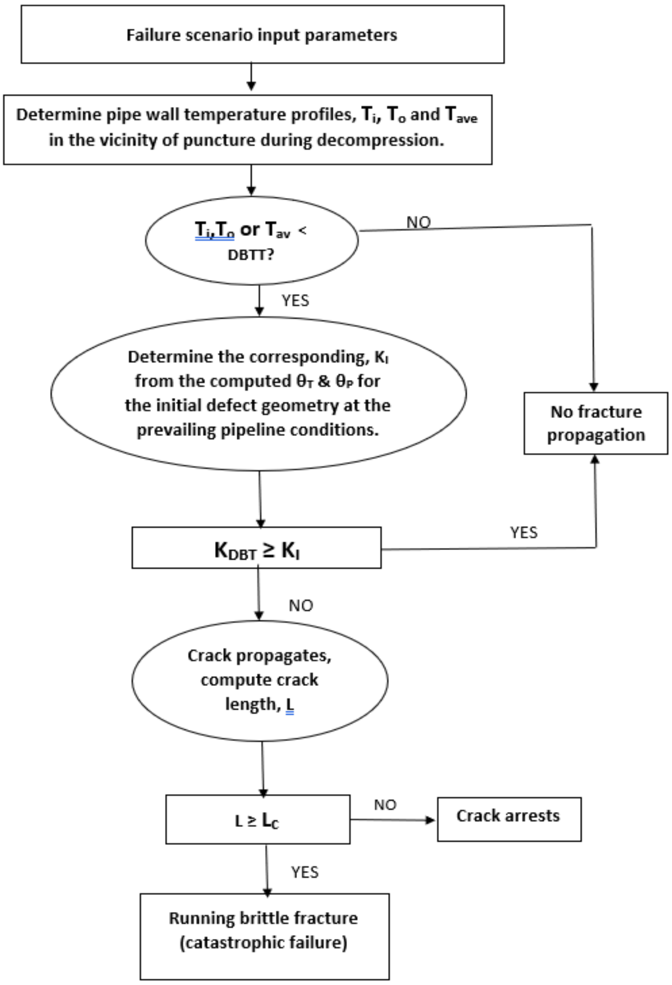
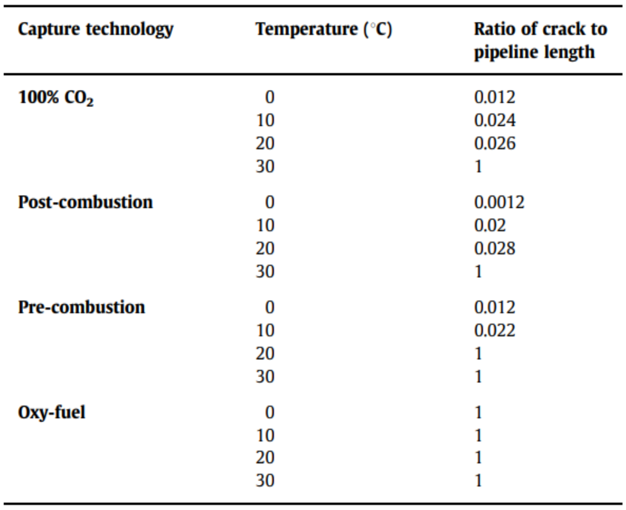


Figure 3. Brittle fracture calculation algorithm. T_i ,T_o , T_{av} = Inner, outer & av. pipe wall temp, K_I= Stress intensity factor, K_{DBT} = Material fracture toughness at DTBT, θ_T = Radial + tangential thermal stresses, θ_p= Radial + tangential pressure stresses, L_c = critical crack length

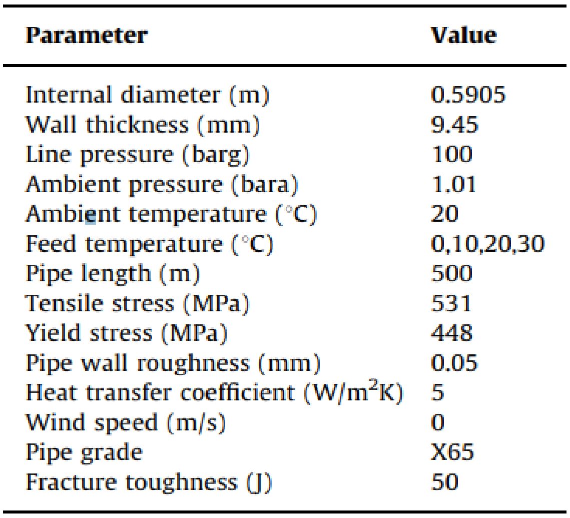
Results & Discussions

Ductile Fracture Investigations: Sample results

Table 1 shows ductile fracture propagation simulation data in the fluid temperature range of 0 to 30ºC at 10ºC intervals expressed in terms of the variation of the ratio of crack length to pipeline length for the various capture technologies including pure CO_2. A ratio of unity means a crack propagating through the entire pipeline length. Table 2 shows the pipeline characterises employed for the above case study.



Capture technology	Temperature (°C)	Ratio of crack to pipeline length
100% CO_2	0	0.012
	10	0.024
	20	0.026
	30	1
Post-combustion	0	0.0012
	10	0.02
	20	0.028
	30	1
Pre-combustion	0	0.012
	10	0.022
	20	1
	30	1
Oxy-fuel	0	1
	10	1
	20	1
	30	1



Parameter	Value
Internal diameter (m)	0.5905
Wall thickness (mm)	9.45
Line pressure (barg)	100
Ambient pressure (bara)	1.01
Ambient temperature (°C)	20
Feed temperature (°C)	0,10,20,30
Pipe length (m)	500
Tensile stress (MPa)	531
Yield stress (MPa)	448
Pipe wall roughness (mm)	0.05
Heat transfer coefficient (W/m^2K)	5
Wind speed (m/s)	0
Pipe grade	X65
Fracture toughness (J)	50

Table 1. Ductile fracture propagation simulation data for different CO_2 composition streams

Table 2. Pipeline characteristics and prevailing conditions for ductile fracture simulation

Brittle Fracture Investigations: Sample results

Figure 4 shows the variation of the pipe wall temperature in the proximity of a 20 mm puncture for different CO_2 compositions typical of the various capture technologies including pure CO_2 after 10,000 s of depressurisation. As it may be observed, along with a significant drop in the pipe-wall temperature, in contrast to ductile fracture behaviour, within the ranges tested, the pipeline's propensity to brittle fracture is marginally impacted by the CO_2 stream composition.

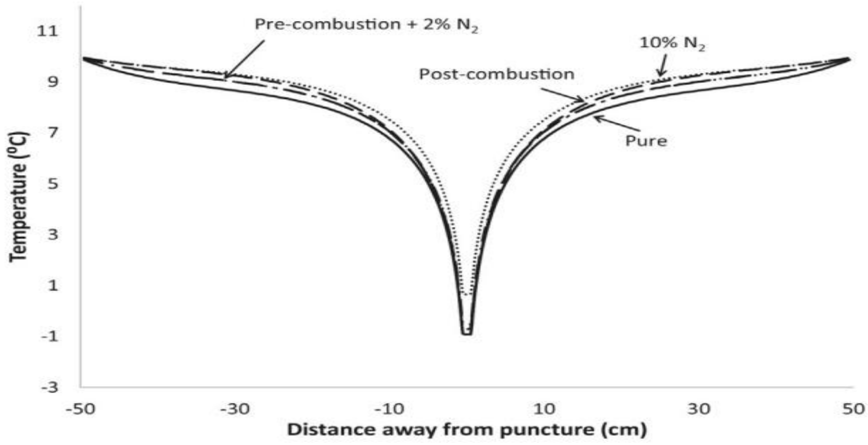
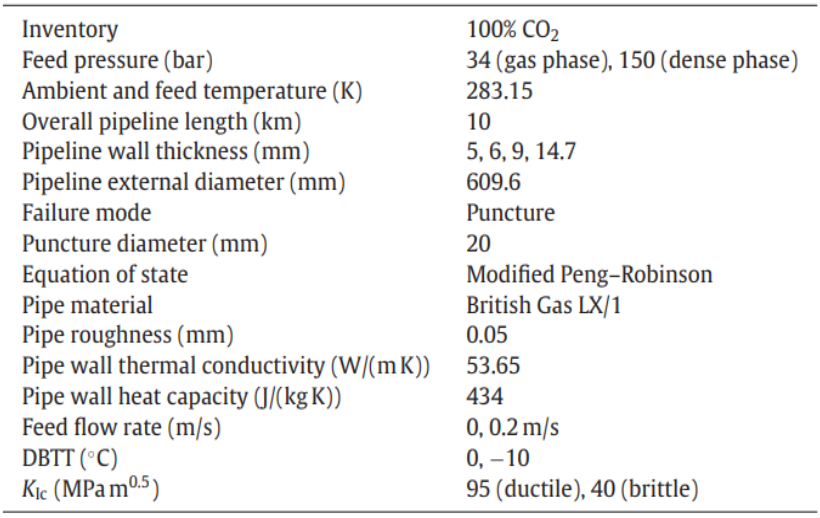


Figure 4. The variation of the temperature profile in the proximity of a 20 mm through wall defect at 10,000 s following depressurisation for various CO_2 stream impurities

[5] Mahgerefteh, h., Brown, S. and Denton, G., 'Modelling the impact of stream impurities on ductile fractures in CO2 pipelines', Chem.Eng.Sci., 74, 2012, 200-210.
[6]. Mahgerefteh, h., Zhang, p., and Brown, S., 'International Journal of Greenhouse Gas Control, 46, 2016, 39-47.
[7} PipeTech Pipeline rupture failure consequnce analysis computer programme, https://pipetechsoftware.com/



Inventory	100% CO_2
Feed pressure (bar)	34 (gas phase), 150 (dense phase)
Ambient and feed temperature (K)	283.15
Overall pipeline length (km)	10
Pipeline wall thickness (mm)	5, 6, 9, 14.7
Pipeline external diameter (mm)	609.6
Failure mode	Puncture
Puncture diameter (mm)	20
Equation of state	Modified Peng–Robinson
Pipe material	British Gas LX/1
Pipe roughness (mm)	0.05
Pipe wall thermal conductivity (W/(m K))	53.65
Pipe wall heat capacity (J/(kg K))	434
Feed flow rate (m/s)	0, 0.2 m/s
DBTT (°C)	0, −10
K_{Ic} (MPa $m^{0.5}$)	95 (ductile), 40 (brittle)

Table 3. Pipeline characteristics and prevailing conditions for brittle fracture simulations.

Conclusion

The safe operation of high-pressure CO_2 transportation pipelines is of paramount importance to the success of CCUS as a viable technology for tackling global warming. In this paper, we presented the main features of fluid-structure interaction models along with their applications for simulating brittle and ductile fractures in CO_2 pipelines containing the various CO_2 impurities typical of post-combustion, pre-combustion and oxyfuel technologies. The results show that both the fluid temperature and the CO_2 composition have a profound impact on the pipeline's propensity in undergoing ductile fracture failure. In contrast, in the case of brittle fracture propagation, within the ranges tested, despite a significant drop in the pipeline temperature profile in the proximity of the puncture posing the risk of brittle fracture failure, the CO_2 mixture composition has a marginal impact on the brittle fracture failure.

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