Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 3123 – 3130

Energy Procedia

GHGT-11

Design overview of high pressure dense phase CO_2 pipeline transport in flow mode.

Kumar Patchigolla*, John E. Oakey

Centre for Energy and Resource Technology, Cranfield University, UK, MK43 0AL

Abstract

In open literature, there is little information available with regards to the engineering and technological issues for material corrosion, in relation to high pressure supercritical CO_2 pipeline transport from single point sources, such as the power industry. A typical CO_2 pipeline is designed to operate at high pressure in the dense phase. However, it is evident that although there is considerable experience of testing materials in lower pressure gaseous CO_2 in the oil and gas industry, there is little understanding of the behaviour of pipeline materials when in contact with impure CO_2 captured either from power plants or the oil and gas industry.

In this particular project development, a dynamic dense phase CO_2 corrosion rig has been built (conditions: ~85 bar, 40 ^{o}C and up to 5 l/min flow rate) in flow mode, to understand the effect of impurities (SO_2, O_2, H_2, NO_2 & CO) present in captured CO_2 on the pipeline transport materials. This unique facility in the UK was developed via the MATTRANS project funded by the E.ON-EPSRC strategic partnership (EP/G061955/1). The test rig includes different metallic materials (X grade steel: X60, X70 and X100) to assess the corrosion of pipelines, and different geometry components (tubes, plates, charpy and tensile coupons), to assess ageing and decompression behavior of polymeric seals (Neoprene, fluorocarbon, ethylene and Buna N) under water-saturated dense phase CO_2 with different impurity concentrations (0.05 mol % SO_2; 4 mol % O_2; 2 mol % H_2; 0.05 mol % NO_2; 1 mol % CO). The dynamic data generated from this dense phase CO_2 corrosion rig will give vital information with regards to pipeline suitability and lifetimes, when operating with dense CO_2.

Keywords:Pipeline transport, material issues, dense phase CO2,polymeric seals

1. Introduction

* Corresponding author. Tel.:+44 (0)1234 750111; fax: (+44) (0)1234 754036
E-mail address: k.patchigolla@cranfield.ac.uk

1876-6102 © 2013 The Authors. Published by Elsevier Ltd.
Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.198

The capture of CO_2 from power plants is a proposed method to reduce the release of CO_2 to the atmosphere. Particularly, the CO_2 transport system plays a key role in linking the capture and storage of carbon systems. For CO_2 transport systems, the materials challenges lie in establishing the requirements for a system where CO_2 is the major component and not an impurity, as in the oil and gas industry. Whilst a lot of effort has addressed the problem of carbon dioxide corrosion ('sweet' corrosion) in pipelines used for oil and gas transport, little work has focused on corrosion associated with CO_2 as major component. The CO_2 pipelines in USA have reported no significant pipeline failures due to internal corrosion. But this mainly depends on water content in the CO_2 in the pipeline. In terms of pipeline design and operations, a dewatering process and water monitoring system is recommended. Dry CO_2 does not cause corrosion in the carbon steel generally used in pipelines under ordinary circumstances. If the CO_2 cannot be dried it can still be transported through corrosion resistant steel that would safely take other contaminants, but this will significantly increase the cost of the pipeline. Open literature indicated that carbon steel is the most attractive alternative for long distance pipelines and that 13% Cr steels can be considered for shorter distance pipelines for CO_2 transport. However, in locations where contact with wet CO_2 is more likely or unavoidable *e.g.* inlet piping to compressors, coolers and scrubbers, then it becomes economical to select a corrosion resistant alloy (CRA). The CO_2 stream ought preferably to be dry and free of hydrogen sulphide because only very low levels of toxic contaminants such as H_2S would be acceptable, in case of leakage.

CO_2 can cause deterioration and explosive expansion on non-metallic materials (elastomers) which were majorly studied in open literature and specified in the oil and gas industry. Several studies [1] recommended that the currently specified CO_2 (based on oil and gas industry) seal materials need to be tested to ensure their suitability for the CO_2-rich compositions expected from the capture plants. In that context, recently UK academics have been awarded a joint EPSRC-E.ON partnership project which covers materials research for next generation CO_2 transportation (MATTRAN). In the MATTRAN project [2] researchers are testing the several non-metallic seal materials under CO_2 rich compositions, with and without impurities.

1.1 Current experience with CO_2 pipeline transport

At present, the only experience with large scale, long distance CO_2 transport exists in the oil industry, namely in enhanced oil recovery (EOR), where the CO_2 is used to displace oil in the underground reservoirs and thus enhance the oil yields. In the EOR [3] industry, CO_2 pipelines have been used since the early 1970s and at present the CO_2 pipeline network in North America stretches for over 2500 km and its total transport capacity is nearly 50 Mt CO_2 yr^{-1}. The longest pipeline in this network is the 808 km long Cortez pipeline from Cortez in Colorado to Denver City in Texas. Selected existing long-distance pipelines are listed in Table 1

All the existing large-scale CO_2 pipelines are designed for dense phase/supercritical conditions, i.e. a CO_2 pressure above 7.38 MPa. The typical operational intervals for temperature and pressure of the CO_2 are 15-30 °C and 10-15 MPa respectively [4].However, due to the special properties of CO_2 and normal pressure drops in pipeline, it is not easy to maintain the CO_2 within these ranges. CO_2 has to be regularly recompressed along the route. Further, the compressibility and density of CO_2 show strong, nonlinear dependence on the pressure and temperature, which makes it difficult to fully predict the CO_2 flow. At the critical point of CO_2 (7.38 MPa and 31 °C) even a small change in temperature or pressure yields a large change in density (e.g., the density doubles with a change in temperature from 47 to 37 °C at a constant pressure of 9 MPa). In addition to the pipeline operating parameters (i.e., temperature and pressure), the amounts of impurities present in the CO_2 stream also affect its physical properties and can have considerable impact on pipeline design and operation. The majority of the CO_2 pipelines currently in use for transport of CO_2 are derived from naturally occurring sources. As a result, the composition of the gas stream can be considerably different than in CO_2 streams resulting from CO_2 capture technologies linked with power plants. Table 2 shows examples of gas composition in several existing pipelines transporting CO_2 from both natural and industrial sources.

Table 1: Existing long-distance CO_2 pipelines.

Pipeline	Location	Operator	Capacity [$MtCO_2$ yr^{-1}]	Length [km]	Year finished	Origin of CO_2
Cortez	USA	Kinder Morgan	19.3	808	1984	Mc Elmo Dome
Sheep Mountain	USA	BP Amoco	9.5	660	-	Sheep Mountain
Bravo	USA	BP Amoco	7.3	350	1984	Bravo Dome
Canyon Reef Carriers	USA	Kinder Morgan	5.2	225	1972	Gasification plants
Val Verde	USA	Petrosource	2.5	130	1998	Val Verde Gas Plants
Bati Raman	Turkey	Turkish Petroleum	1.1	90	1983	Dodan Field
Weyburn	USA & Canada	North Dakota Gasification Co.	5	328	2000	Gasification plant
Total			49.9	2591		

Table 2: CO_2 stream composition in existing pipelines [5]

	Canyon Reef Carriers	Central Basin Pipeline	Sheep Mountain	Bravo Dome	Cortez Pipeline	Weyburn	Jackson Dome
CO_2	85-98	98.5	96.8-97.4	99.7	95	96	98.7-99.4
CH_4	2-15	0.2	1.7	-	1-5	0.7	Trace
N_2	<0.5	1.3	0.6-0.9	0.3	4	<300 ppm	Trace
H_2S	<200 ppm	<20 ppm wt	-	-	0.002	0.9	Trace
C_2+		-	0.3-0.6	-	Trace	2.3	-
CO	-	-	-	-	-	0.1	-
O_2	-	<10 ppm wt	-	-	-	<50 ppm wt	-
NO_x	-	-	-	-	-	-	-
SO_x	-	-	-	-	-	-	-
H_2	-	-	-	-	-	Trace	-
Ar	-	-	-	-	-	-	-
H_2O	50 ppm wt	257 ppm wt	129 ppm wt	-	257 ppm wt	20 ppmv	-

2 Experimental methodologies

2.1 Transport flow loop rig

The dynamic high pressure flow loop rig will be used to generate engineering data, test flow measurement devices, and test non-metallic materials degradation in different CO_2 contaminant environments. This facility can generate data in gas, liquid and dense phase CO_2 test conditions. It comprises a feed compressor, circulation pump, automatic back pressure regulator, viewing cell, temperature conditioning unit and safety interlocks. The total volume of transport flow in the rig is approximately 3 litres and is made from stainless steel 316. Different geometrical specimens and nonmetallic materials, shown in Figure 1, were mounted into the transport flow rig. The test specimens were machined from X60, X70 and X100 plates and the specimens were ground with 600 grit silicon carbide paper. The weight was measured using a balance with a precision of 0.1 mg. After the specimens were mounted, the dense phase CO_2 saturated with water is circulated through these specimens for 1000's of hours. The pressure, temperature and impurities composition were maintained throughout the experiments and the phase behavior changes was observed through view cell. Electrochemical measurements started immediately after the experimental condition was obtained.

The transport rig will address the long term materials data (1000's of hours) including operating cycle conditions, likely damage mechanisms such as pitting, corrosion fatigue, SCC, H_2 embrittlement and weld cracking. Figure 1 & 2 shows the mechanism of mounting the corrosion coupons inside the transport rig and its process flow diagram. The corrosion rate was monitored continuously using the LPR technique and weight loss was recorded after the end of the experiments. The corrosion rate for the weight loss method can be calculated by the following equation 1 [6].

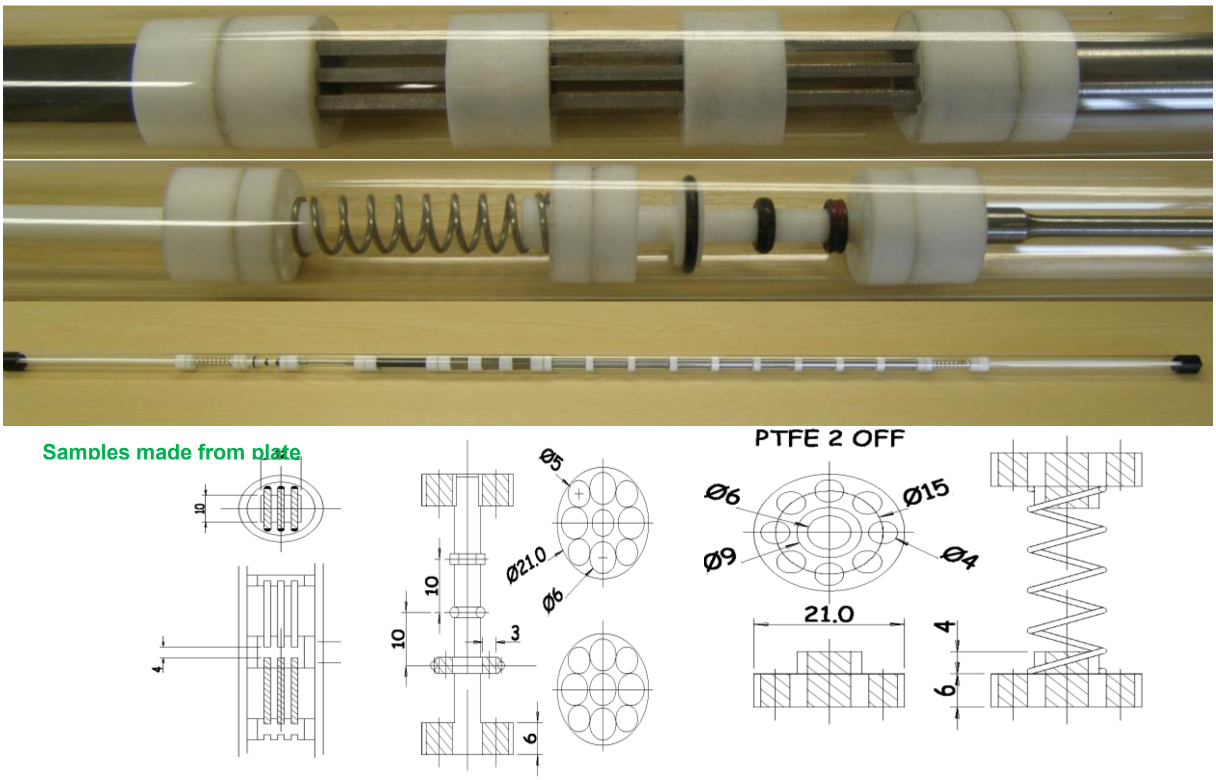

Figure 1 The mounting mechanism of corrosion coupons in transport flow rig.

Corrosion rate (mm/y) = (8.76E4 x weight loss, g)/(area, cm^2 X density, g/cm^3 X time, hours) (1)

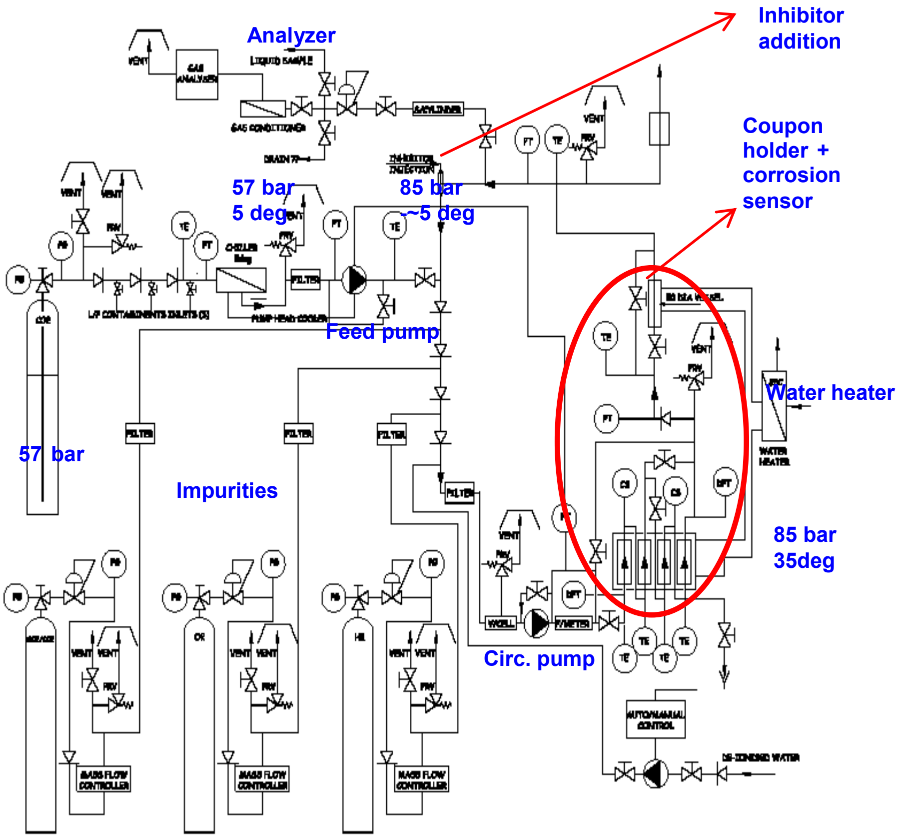

Figure 2 Process flow diagram of transport flow rig

2.2 Experimental rig specification

Figure 3 shows the automated transport rig and its components. . The specification of the rig components are as follows:

- Transport flow loop rig operates above 80 bar, 35 deg (capable of up to **700 bar, -50 to 150 deg C)** in flow mode
- Runs for several hundred hours depends on material corrosion and environment
- **Effective measurement and monitoring**
  - ✓ **Continuous monitoring** of corrosion by electro chemical noise & ~~L~~ linear polarization resistance
  - ✓ Offline/online gas composition measurement **(infrared, mass spec)**

  - ✓ **Incorporating flow meters-venturi, orifice (up to 50mm diameter)**

- ➢ Rig includes several coupon geometry—plates, tubes, bar, charpy and tensile coupons
- ➢ Impurities– **H_2O, H_2, H_2S, NOx, $SO_2$and O_2 etc..**
- ➢ Materials– X60, X70, X80, X100, 316, duplex steel etc..
- ➢ Non-metallic materials degradation—seals, lubricants
  - ✓ Buna N, Ethylene Propylene, Neoprene and Fluorocarbon

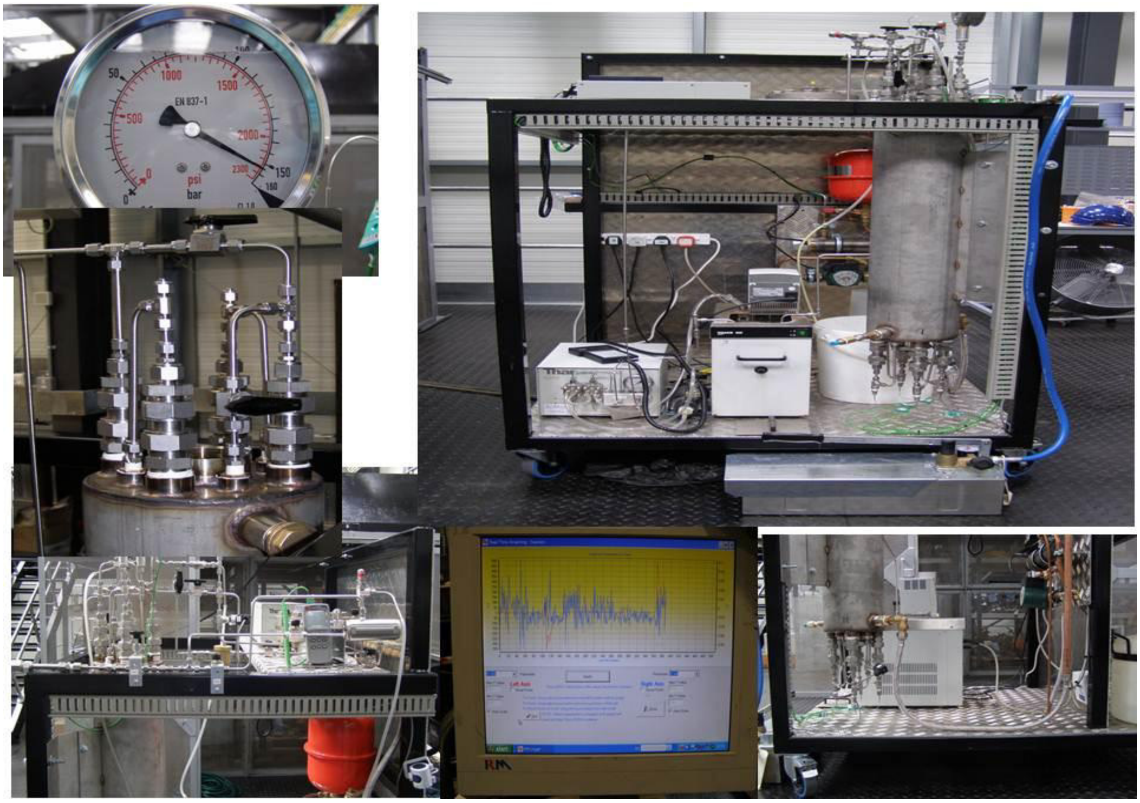

Figure 3: Several micro photographs of the transport flow rig at Cranfield University.

2.3 Experimental testing composition

As the future CO_2 transport networks will have to deal with CO_2 from a number of different sources, it is important to identify the likely impurities present in the CO_2 streams from different energy conversion and CO_2 capture technologies. The MATTRAN project attempts to briefly summarise existing knowledge of impurities resulting from different technologies. The technologies critically reviewed are: Oxy-fuel combustion, Post-combustion capture and Pre-combustion capture. After careful thought, Cranfield undertaking this work to improve the understanding of the CO_2 pipeline failures and corrosion rates with various CO_2 stream impurities, have outlined the key impurities to be investigated,, as shown in Table 3.

Table 3 Component mixtures used for testing materials failure

Impurity	***Level (%)***	***Failure mechanism/likely source***
NO_2	*0.05*	*Selected to understand the materials behaviour;* *Realistic composition from Oxy-fuel capture plant.*
SO_2	*0.05*	*Might lead to sulphide corrosion (presence of water);* *Health and safety issues/challenges.*
H_2S	*0.05*	*Material degradation/ H2S corrosion cracking; Embrittlement;* *Composition from pre combustion capture plant*
H_2	*2*	*Embrittlement of the material; Health and safety issues;* *Hydrogen induced cracking; Pre-combustion capture plants;* *Cracks from cathodic protection*
O_2	*4*	*No studies available; Issues associated with corrosion mechanisms;* *From oxy-fuel capture plant;*

2.4 Surface characterization

Following the termination of the experiments, the specimens were inspected through microscope for localized attacks. Some of the specimens were analyzed in a scanning electron microscope using a cross-section of the specimen.

2.5 Pipeline risks and mitigation strategies

- CO_2 is not explosive or inflammable like natural gas
- CO_2 is denser than air and might accumulate in depressions (in case of CO_2 leakage)
- High concentrations of CO_2 might have negative impacts on humans (asphyxiation) and ecosystems.
- pipeline rupture.

Pipeline system needs number of safety systems includes:

- Leak/rupture detection- CO_2 leakage can be reduced by decreasing distance between safety valves
- Measurement of T,P and flow-rates by telemetry (provides early detection of potential problems)
- Instrument to detect corrosion or other defects
- Safe de-compression of the pipeline- control closing of block values and/or safety shutdown systems

3 Conclusions

The main aim of this paper was to provide the design overview of a high pressure, dense phase CO_2 transport flow loop rig to understand the pipeline materials. This unique facility looked at design parameters of the pipelines and selected appropriate materials and operating conditions to control corrosion and non-metallic degradation in pipelines carrying dense phase CO_2 from the capture processes. In this context, this paper has critically reviewed the component mixtures to be used for testing the corrosion mechanisms.

References

1. Oakey JE, Kara F, Patchigolla K. The effects of impurities for capture technologies on CO_2 compression and transport. BCURA Report B93, 2010
2. EPSRC-EON partnership project, Materials for next generation CO_2 transportation, http://research.ncl.ac.uk/mattran/
3. US Department of Energy, 2004 Enhanced oil recovery/CO_2 injection Office of Science, Office of Fossil Energy, http://www.fe.doe.gov/programs/oilgas/eor/
4. Stevensson, M. Odenberger, F. Johnsson, L. StrömbergTransportation Infrastructure for CCS – Experiences and expected development, 2005: Proceedings of the 7th International Conference on Greenhouse Gas Technologies (GHGT-7), September 5-9, 2004, Vancouver, Canada, v.II, 2531-2534
5. Steele R, Kesseli J, Baldwin P, 2005 Insertion of shock wave compression technology into micro turbines for increased efficiency and reduced costs ASME, Turbo Expo 2005
6. ASTM Standard G 31, Standard practice for laboratory immersion corrosion testing of metals, in Annual Book of ASTM Standards, vol. 03. 02 (West Conshohocken, PA: ASTM International, 1994)