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On the potential for interim storage in dense phase CO_2 pipelines

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ABSTRACT

This paper investigates the flexibility that exists within a dense phase carbon dioxide (CO_2) pipeline system to accommodate upset conditions in the Carbon Capture and Storage (CCS) network by utilising the pipeline as a storage vessel whilst still maintaining flow into the pipeline. This process is defined in the pipeline industry as "line-packing" and the time available to undertake line-packing is termed the line-packing time. The longer the line-packing time, the more resilient the pipeline system is to flow variations or short term operational issues at the capture or storage site. The aims of the study were; to investigate the impact of typical CO_2 pipeline design parameters (diameter, wall thickness and length) as well as CO_2 mass flow rate and pipeline inlet and outlet pressure on the available line-packing time and; to derive relationships between the key variables to allow designers to optimise the line-packing time for a pipeline system.

The study was undertaken by developing a viable study set of dense phase CO_2 pipelines using steady state hydraulic analysis and stress based design principles. The study set was designed to cover the range of design parameters, flow rates and pressures considered to be typical of dense phase pipelines in CCS systems. For each of the pipelines in the study set, the line-packing time was calculated using a transient hydraulic analysis approach. Although by interrogating the results, individual relationships could be identified between key input parameters and the line-packing time, the integration of all of the critical parameters could not be achieved through simple regression analysis techniques. Consequently, using the dataset of pipelines and line-packing times developed, an Artificial Neural Network (ANN) was designed to enable a comprehensive sensitivity analysis of the line-packing time to the input data to be conducted. It is also demonstrated how the ANN can be used as a design tool for the prediction of line-packing time.

As would be expected, the line-packing capacity of the pipeline can be increased by increasing the available internal volume of the pipeline, reducing the mass flow rate into the pipeline, increasing the allowable operating stress and managing the inlet pressure and outlet pressures. However, one of the key findings of the work is that, in the dense phase, line-packing times of only up to 8 h can be achieved for pipeline dimensions typical of those considered for CCS schemes. Consequently it has been confirmed that the pipeline does not represent a long-term storage option for CCS systems.

However, if line-packing capability is considered at the design stage then the level of flexibility for the pipeline to act as short-term storage in the network increases. In particular, it is recommended that the effect of increasing the wall thickness on the line-packing time is considered at the design stage to determine the benefits of this option in enabling the pipeline to be used as a short-term storage option in the CCS system and prevent venting of CO_2 during short-term outage events at the capture or storage site.

1. Introduction

Carbon Capture and Storage (CCS) has drawn significant attention in the last decade as one solution to reduce the emissions of Carbon Dioxide (CO_2) into the atmosphere and decelerate, and potentially reverse, the rate of global warming. This is achieved by capturing CO_2 from large sources such as thermal power plants, refineries and other industrial sites and transporting it, predominantly by pipeline, to

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geological sites for either permanent storage or for use in Enhanced Oil Recovery (EOR) schemes.

When designing a CCS network, the capture plants, pipeline system and storage sites are selected to comply with specific site and design constraints. As more renewable energy becomes available to the electricity grid, CO_2 capture plants at power stations will have to operate flexibly to accommodate the variable contribution of renewable energy. Operation of the capture plant could then lead to daily and seasonal variations in CO_2 flow being sent through a CCS network, and the pipelines must be designed to accommodate all these variations in flow. The storage site can impose additional variability and constraints on the pipeline, for example, due to maintenance at the injection point or changes in injection rate (Sanchez Fernandez et al., 2016b). Although this study concentrates on variation in flow due to power plant operation, intermittent supply of CO_2 is also expected from industrial sources of CO_2. Therefore, a pipeline network needs to be able to respond to and accommodate all of these kinds of transient variations in CO_2 flow.

A considerable body of published literature is dedicated to the identification of transient operation scenarios that could occur during the operating life of a pipeline in a CCS chain. For example, Wiese et al. (2010), Nimtz et al. (2010), Klinkby et al. (2011) and Uilenreef and Kombrink (2013) discuss supply and demand fluctuations, start-up and shutdown after a planned outage and start-up after a non-planned (emergency) shutdown. The broad objective of this paper is to investigate the flexibility that exists within the pipeline network to accommodate short-term changes in CO_2 flow, primarily due to flow variations or short term operational issues, through the use of pipeline line-packing.

The term line-packing is most generally used to describe the storage capabilities of natural gas pipelines during times when the pipeline is temporarily used as a storage vessel. In natural gas transportation, line-packing introduces a degree of operational flexibility and offers some variable capacity during possible upsets and supply variations in a system. During line-packing, the flow of fluid out of the pipeline is stopped by closing (or throttling) a downstream valve whilst still allowing fluid to flow into the pipeline upstream. As a result, the fluid contained in the pipeline is compressed (packed) and the pressure of the contained fluid within the pipeline increases until the downstream valve is opened. The amount of line-packing achievable is limited by the Maximum Allowable Operating Pressure (MAOP) of the pipeline.[1] Currently there is no methodology for assessing the line-packing characteristics of dense phase CO_2 pipelines. Hence, the focus of this work is to determine the relevance of line-packing as a strategy for dense phase CO_2 pipelines and to assess whether the pipeline is effectively able to accommodate variations in the upstream and downstream constraints on the system.

In this study, the flexibility to line-pack a pipeline is assessed by determining the time available for an operator to store dense phase CO_2 in the pipeline before having to shut down the pipeline and potentially vent CO_2 at the capture plant. This time period is termed the "line-packing time". Natural gas benefits from a significantly higher compressibility factor than CO_2; therefore line-packing is an established and proven tool in natural gas applications. Consequently, the available line-packing time for natural gas pipelines is not an operational concern and the open literature on this subject is mainly devoted to optimisation and management of the line-packing in natural gas pipeline networks (Carter and Rachford, 2003; Krishnaswami et al., 2004; Borraz-Sanchez, 2010; Rios-Mercado and Borras-Sanchez, 2015). However, in the dense phase, CO_2 has a relatively low compressibility compared with gaseous phase CO_2 or natural gas, and therefore during the line-packing of a dense phase CO_2 pipeline, the pressure will more rapidly approach the pipeline's MAOP and the line-packing time needs to be carefully considered. Pipeline transportation systems have traditionally been designed using steady-state analysis, as this was found to be sufficient for the design optimisation of relatively stable supply and demand scenarios. The same philosophy applies to CO_2 pipelines operating in the United States where a relatively constant supply and demand scenario exists (Seevam, 2010). In CCS situations, where sources of CO_2 are predominantly from power plants and industrial sources, the pipelines will have to accommodate a more transient flow of CO_2, which will vary with the power plant load cycle or industrial site operating regime, and this needs to be considered at the design stage.

The current study will investigate the impact of pipeline design parameters (diameter, wall thickness and length) as well as CO_2 mass flow rate and pipeline inlet and outlet pressure on the available line-packing time with the aim of providing a design tool that can be used to study the effects of the pipeline design parameters on line-packing time. It is recognised that the inlet temperature of the fluid will also affect the line-packing time due to its effect on compressibility and fluid density. However, this parameter was not included in this study as it is considered that the inlet temperature will be set by other constraints determined by the composition of the fluid, such as decompression behaviour and corrosivity (Cosham et al., 2012; Race et al., 2012), and therefore was not considered as a design variable in this study. The inlet temperature was kept constant for all scenarios at 30 °C (Wetenhall et al., 2014a).

The study has been undertaken by developing a viable study set of dense phase CO_2 pipelines using steady state hydraulic analysis and stress based design principles. This procedure is described in Section 2. For each of the pipelines in the study set, the line-packing time was calculated using a transient hydraulic analysis approach (Section 3). Although individual relationships could be identified between key input parameters and the line-packing time using the output of the transient analysis, it was found that multifactorial analysis techniques were required to undertake a comprehensive sensitivity analysis and develop the design tool. Consequently, an Artificial Neural Network (ANN) was designed to fulfil these objectives. The development of the ANN, the results of the sensitivity analysis and the demonstration of the use of the ANN as a design tool are explained in Section 4.

All of the modelling in this paper has been conducted assuming 100% pure CO_2. It has been shown that the addition of common impurities into the CO_2 stream decreases the density of the stream (Wetenhall et al., 2014b) and therefore the pure CO_2 case represents the worst case scenario.

2. Steady state pipeline analysis

Steady state hydraulic modelling is primarily used for facility selection, such as compression or pumping distances and pipeline sizing, and is carried out by analysing flow rates, pressure drops, pipeline capacity and corresponding diameter requirements (Mohitpour et al., 2007). In this work, a steady state analysis approach has been used to select a study set of pipelines with different diameters and wall thicknesses for use in the line-packing analysis. The dimensions of the pipelines selected must satisfy two design criteria; firstly the internal stress must not exceed the maximum allowable stress in the pipeline (a stress based criteria) and secondly the CO_2 in the pipeline must remain in single phase (a hydraulic criterion). The methodology adopted for the selection of pipe dimensions using these criteria is described in detail in the following sections and represented diagrammatically in Fig. 1.

2.1. Selection of flow rate

The baseline mass flow rate for this study is based on capturing 90% of the emissions of a reference emitter. The selected reference emitter,

[1] The MAOP is the maximum pressure at which a system can be operated continuously under normal conditions at any point along the pipeline PD8010-1 (2015).

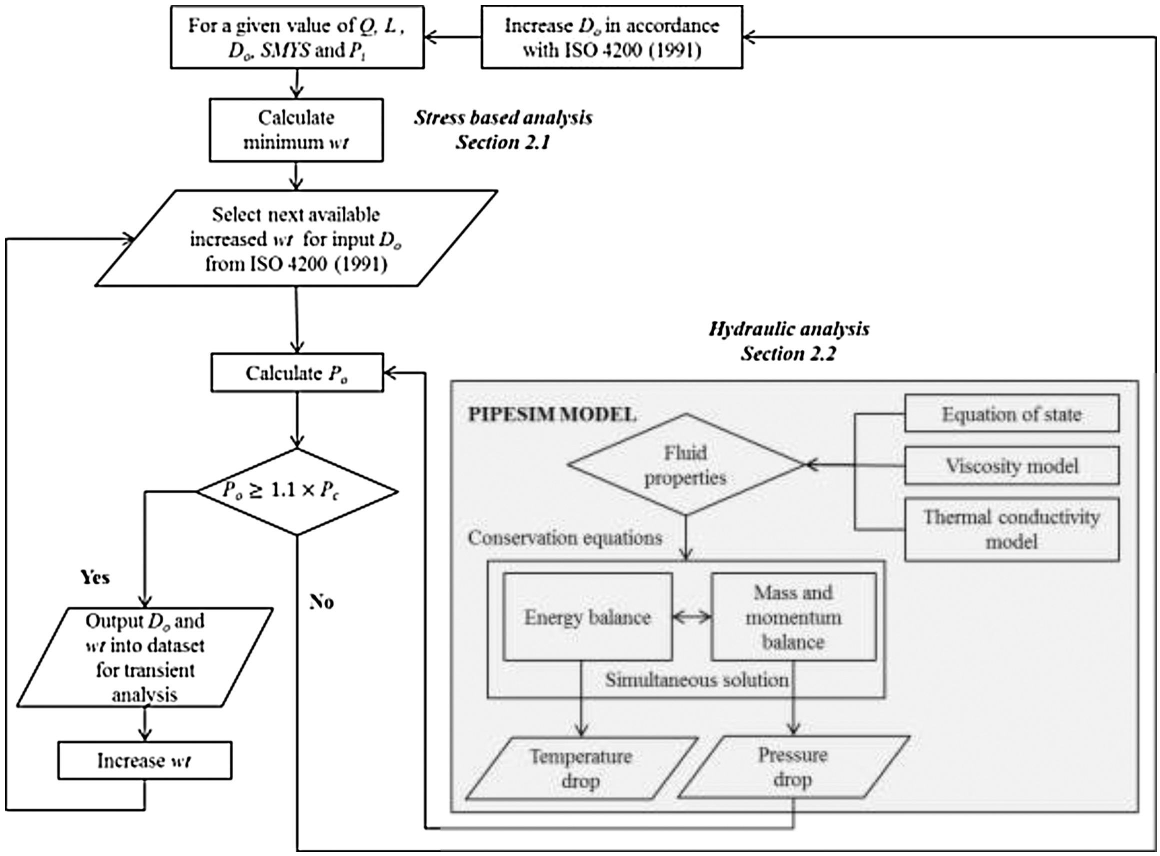


Fig. 1. Flow diagram indicating the procedure and calculations conducted in the static analysis to select the pipeline dimensions for the transient analysis.

described in detail in (Sanchez Fernandez et al., 2014) is an advanced supercritical pulverized coal (ASC PC) power plant with specific emissions of 771.9 kg/MWh_{net} and a power output of 819 MW gross. A CO_2 capture unit based on mono-ethanol amine (MEA) technology is integrated downstream of the power plant and is designed to capture 90% of the CO_2 present in flue gas. At full power plant load after capture, the CO_2 mass flow into the pipeline is calculated to be 150 kg/s. For base load operation, the power plant is designed to operate continuously at full load with only major shut downs for maintenance, which results in 7500 operation hours per year and a CO_2 flow to pipeline of 4 $MtCO_2$ per year.

Another important aspect is the minimum CO_2 flow that can be safely sent to the pipeline without shutting down the CO_2 compressor. In the reference emitter selected, the use of integrally geared centrifugal compressors with inlet guide vane systems was considered. The inlet guide vane system (IGV) manipulates the angle between the inlet flow and the compressor impeller and, therefore, the relative speed of the inlet gas. This system is used to control compressor performance when the inlet conditions change. The part load operation of these compressors for CO_2 capture has been studied by Sanchez Fernandez et al. (2016a), providing the performance curves for varying input mass flow. The authors concluded that the IGV system can provide a constant discharge pressure of 110 bar for an actual mass flow inlet to the compressor of at least 76% of the design flow. The compressor isothermal efficiency varies between 80% and 77% for this flow range. For this work, three identical compressors with a maximum mass flow capacity of 50 kg/s were assumed to work in parallel and the performance curves provided by Sanchez Fernandez et al. (2016a) were used to determine discharge conditions for different inlet mass flows. Each compressor has a minimum actual mass flow of 35 kg/s before reaching surge conditions and shut-down.

The maximum inlet mass flow rate to the pipeline was therefore taken as a uniform flow of 150 kg/s (4Mt/year). However, three part-load conditions of 110 kg/s (3.47Mt/year), 70 kg/s (2.21Mt/year) and 35 kg/s (1.10Mt/year), where also studied.

2.2. Selection of pipeline dimensions: stress based criterion

Pipeline lengths of 50 km, 100 km and 150 km were chosen for the study as these were considered to be relevant lengths for an onshore CCS pipeline network in the UK. No elevation change was considered in the steady state analysis. Five outside diameters (457 mm, 508 mm, 559 mm, 610 mm and 914 mm) were selected using available pipeline sizes from ISO 4200 (1991), taking due consideration of the pipeline lengths and flow rates that had been chosen for the study. The pipeline diameters selected are within the range of pipeline diameters that are currently operational within the USA (Table 1) and have been considered for onshore CO_2 pipelines in the UK (IEAGHG, 2013). Selecting a range of pipeline diameters for the analysis allows the impact of

Table 1
Existing long distance pipelines transporting dense phase CO_2 (Race et al., 2007; Vandeginste and Piessens, 2008).

Pipeline	Location	CO_2 Capacity (Mt/year)	Length (km)	MAOP (bara)	Diameter (mm)
Cortez	USA	19.3	808	186	760
Sheep Mountain	USA	9.5	660	132	508/610
Bravo	USA	7.3	350	165	510
Canyon Reef Carriers	USA	5.2	225	140	406
Weyburn	USA/Canada	5	328	186/204	300/360

oversizing pipelines on network flexibility and line-packing to be studied.

The required wall thickness for each pipeline diameter was determined using the stress based design criterion outlined in PD8010-1 (2015). In this approach the hoop stress, σ_h (in MPa) is calculated for thin wall pipe using Eq. (1):

$$\sigma_h = \frac{p \times D_0}{2 \times wt} \tag{1}$$

where, p is the internal pressure, D_0 is the outer diameter (OD), and wt is the wall thickness. The calculated design stress has to comply with the stress based design criteria given by:

$$\sigma_h \leq e \times a \times \sigma_{SMYS} \tag{2}$$

where e is the weld factor (assumed to be 1), a is the design factor and σ_{SMYS} is the Specified Minimum Yield Stress (SMYS) of the pipeline steel in MPa. In this study the design factor was set to be 0.72 (Wetenhall et al., 2014a). Consequently, the maximum stress in the pipeline was limited to 72% SMYS. The material of construction of the pipeline has been assumed as EN ISO 3183 (2012) L450 carbon steel, having an SMYS of 450 MPa.

An inlet pressure to the pipeline system of 110 bara has been selected. This pressure is considered to be appropriate, given the scale of distances that could be faced in the UK in future developments of CCS networks and has also been used in similar studies (*e.g.* Sanchez Fernandez et al., 2014). Using Eq. (1) it is therefore possible to calculate the minimum wall thickness required to satisfy the stress based design condition. Although EN ISO 3183 (2012) does not specify discrete wall thicknesses, the approach that has been adopted here is to select the standardised pipeline sizes specified in ISO 4200 (1991). Therefore, once the minimum wall thickness has been calculated, the next available increased wall thickness is chosen.

For example, for $D_o = 457$ mm, the minimum wall thickness would be calculated to be 7.76 mm, using the procedure and data described above, and therefore the next standardised pipeline size of 8.0 mm was selected from ISO 4200 (1991). However, it is also possible to select standardised pipe from ISO 4200 (1991) with a larger wall thickness than 8.0 mm for the same outside diameter of 457 mm. Increasing the wall thickness allows the Maximum Allowable Operating Pressure (MAOP), determined through the rearrangement of Eq. (1) shown in Eq. (3), to be increased and therefore increases the capacity for line-packing in the pipeline.

$$MAOP = \frac{2 \times wt \times \sigma_h}{D_0} \tag{3}$$

The maximum value of σ_h is given by Eq. (2). Therefore, in the example where $D_o = 457$ mm, the minimum wall thickness would be 8.0 mm, but additional wall thicknesses of 8.8 mm, 10 mm and 11 mm could also be selected. This approach also takes into consideration situations where other design constraints, such as the requirement to prevent ductile fracture propagation (Race et al., 2012), may result in an increase in wall thickness above that required for a stress based design. The number of additional wall thicknesses that could be selected for a given diameter was dependent on the hydraulic constraints to avoid two phase flow explained in Section 2.3.

2.3. Selection of pipeline dimensions: hydraulic criterion

The steady state hydraulic criteria for selection of pipeline dimensions required that the outlet pressure, P_o, remained above the critical pressure of CO_2, with a safety margin of 10%, for all of the model cases considered, *i.e.*

$$P_o \geq 1.1 \times P_c \tag{4}$$

where P_c, is the critical pressure of the CO_2 stream. The critical pressure for pure CO_2 is 74.1 bara and therefore the outlet pressure had to remain above 81.5 bara. Consequently, a steady state hydraulic analysis was required to calculate P_o. The steady state hydraulic modelling approach adopted in this study followed the practice outlined by Wetenhall et al. (2014a). The calculation of steady state fluid flow in pipelines requires the simultaneous solution of the equations for conservation of mass, momentum and energy. From the solution of these equations, and given two of the parameters of initial pressure, final pressure or flow rate, it is possible to calculate the pressure and temperature drop along the pipeline. In this analysis, for a given mass flow rate, inlet pressure, inlet temperature, pipeline length and internal diameter – the selection of which has been described in Sections 2.1 and 2.2 – the outlet pressure was calculated to ensure single phase flow in the pipeline.

The hydraulic modelling package PIPESIM (Schlumberger, 2012) was used to conduct the steady state hydraulic analysis. The single component Equation of State (EOS) due to Span and Wagner (1996) was selected to provide a relationship between the thermodynamic variables of the system (*e.g.* temperature, pressure and volume) and to describe the state of the system under a given set of conditions. The other models that were selected in this study include the Pedersen viscosity model (Pedersen et al., 1984) and the Beggs and Brill flow model with the Moody friction factor as the flow equation (Wetenhall et al., 2014a). SUPERTRAPP (NIST, 2007) was used to determine fluid thermal conductivity.

The methodology adopted in PIPESIM to calculate the heat transfer coefficient between a horizontal buried pipeline and the ground surface follows the approach of Kreith and Bohn (2001) to define a conduction shape factor, *S,* from which the ground heat transfer coefficient, h_g, is calculated using the equation:

$$h_g = \frac{k_g S}{R} \tag{5}$$

where k_g is the ground thermal conductivity and R is the reference length (taken to be the pipe radius).

The conditions that were used in the modelling are listed in Table 2. At the end of the simulation for each pipeline, the outlet pressure was checked to ensure that the hydraulic criterion of Eq. (4) was satisfied. If the selected wall thicknesses resulted in an outlet pressure below 81.5 bara, then the external diameter was increased in order to achieve single phase flow for all of the pipeline wall thicknesses considered.

2.4. Steady state analysis summary

Using the approach outlined in Sections 2.2 and Section 2.3, a set of 75 pipelines were designed with a range of outside diameters, lengths, wall thicknesses and flow rates as presented in Table 3. The outlet pressure and MAOP are also shown for each of the pipelines considered in the study to demonstrate the application of the stress based and hydraulic criteria. It is highlighted that the smallest diameter pipeline

Table 2
Initial conditions considered for the onshore transportation of the dense phase CO_2.

Parameter	Value	Unit
Horizontal Distance	50, 100 and 150	km
Roughness	0.0457	mm
Ambient Temperature	5	°C
Inlet Pressure	110	bara
Internal Diameter	Table 2	mm
Wall Thickness	Table 2	mm
Inlet Temperature	30	°C
Burial depth	1.1	m
Specific heat[a]	490	J/kg-C
Steel Heat Transfer Coefficient	60.55	$W/m^2/K$
Soil Heat Transfer Coefficient[b]	2.595	$W/m^2/K$

[a] For carbon steel.
[b] Assumed to be constant over the whole pipeline length.

Table 3
Results of steady state and transient analysis for all pipeline designs considered to study the effects of pipeline dimensions and flow rate on line-packing times.

Inlet conditions					Steady state analysis		Transient analysis
					Stress criterion < 72% SMYS	Hydraulic criterion > 81.5 bara	
Pipeline no.	Outer diameter (D_o)/ mm	Wall thickness (wt)/ mm	Length /km	Flow rate (kg/ s)	%SMYS	Outlet pressure (P_o)/bara	Linepacking time/s
1	457	8	50	150	69.8	105.6	135
2	457	8	100	150	69.8	101.3	335
3	457	8	150	150	69.8	97.5	557
4	457	8.8	50	150	63.5	102.3	509
5	457	8.8	100	150	63.5	95.0	1020
6	457	8.8	150	150	63.5	87.8	1559
7	457	10	50	150	55.9	102.1	1007
8	457	10	100	150	55.9	94.6	1938
9	457	10	150	150	55.9	87.2	2853
10	457	11	50	150	50.8	102.1	1402
11	457	11	100	150	50.8	94.6	2665
12	457	11	150	150	50.8	87.0	3885
13	457	11	50	110	50.8	105.7	1604
14	457	11	100	110	50.8	101.7	2976
15	457	11	150	110	50.8	97.7	4320
16	457	11	50	70	50.8	108.3	2314
17	457	11	100	70	50.8	106.6	4155
18	457	11	150	70	50.8	105.0	5887
19	457	11	50	35	50.8	109.5	4320
20	457	11	100	35	50.8	109.1	7294
21	457	11	150	35	50.8	108.7	10522
22	508	8.8	50	150	70.6	105.2	127
23	508	8.8	100	150	70.6	100.9	265
24	508	8.8	150	150	70.6	96.6	458
25	508	10	50	150	62.1	105.2	704
26	508	10	100	150	62.1	100.7	1328
27	508	10	150	150	62.1	96.3	1932
28	508	11	50	150	56.4	105.0	1133
29	508	11	100	150	56.4	100.5	2098
30	508	11	150	150	56.4	95.9	3011
31	559	10	50	150	68.3	107.1	314
32	559	10	100	150	68.3	104.4	566
33	559	10	150	150	68.3	101.7	838
34	559	11	50	150	62.1	107.0	812
35	559	11	100	150	62.1	104.3	1491
36	559	11	150	150	62.1	101.6	2128
37	559	12.5	50	150	54.7	107.0	1522
38	559	12.5	100	150	54.7	104.1	2769
39	559	12.5	150	150	54.7	101.3	3900
40	610	11	50	150	67.8	108.3	353
41	610	11	100	150	67.8	106.6	660
42	610	11	150	150	67.8	105.1	964
43	610	12.5	50	150	59.6	108.2	1175
44	610	12.5	100	150	59.6	106.6	2105
45	610	12.5	150	150	59.6	104.9	2942
46	610	14.2	50	150	52.5	108.2	2038
47	610	14.2	100	150	52.5	106.5	3656
48	610	14.2	150	150	52.5	104.8	5099
49	610	14.2	50	110	52.5	109.0	2386
50	610	14.2	100	110	52.5	108.1	4280
51	610	14.2	150	110	52.5	107.2	6017
52	610	14.2	50	70	52.5	109.6	3464
53	610	14.2	100	70	52.5	109.2	6147
54	610	14.2	150	70	52.5	108.8	8698
55	610	14.2	50	35	52.5	109.9	6112
56	610	14.2	100	35	52.5	109.9	11091
57	610	14.2	150	35	52.5	109.7	16219
58	914	16	50	150	69.8	109.8	335
59	914	16	100	150	69.8	109.6	600
60	914	16	150	150	69.8	109.4	850
61	914	17.5	50	150	63.8	109.8	1466
62	914	17.5	100	150	63.8	109.6	2548
63	914	17.5	150	150	63.8	109.4	3510
64	914	20	50	150	55.9	109.8	3307
65	914	20	100	150	55.9	109.6	5739
66	914	20	150	150	55.9	109.3	7907
67	914	20	50	110	55.9	109.9	3898
68	914	20	100	110	55.9	109.8	6877
69	914	20	150	110	55.9	109.6	9674

(continued on next page)

Table 3 *(continued)*

Inlet conditions					Steady state analysis		Transient analysis
					Stress criterion < 72% SMYS	Hydraulic criterion > 81.5 bara	
Pipeline no.	Outer diameter (D_o)/mm	Wall thickness (wt)/mm	Length /km	Flow rate (kg/s)	%SMYS	Outlet pressure (P_o)/bara	Linepacking time/s
70	914	20	50	70	55.9	109.9	5648
71	914	20	100	70	55.9	109.9	10049
72	914	20	150	70	55.9	109.8	14375
73	914	20	50	35	55.9	110.0	10054
74	914	20	100	35	55.9	110.0	18746
75	914	20	150	35	55.9	110.0	27718

chosen (457 mm) with the largest wall thickness (11 mm), just satisfies the hydraulic single phase flow condition (P_o = 87.0 bar) for the longest pipeline length and the maximum flow rate and therefore there is little spare capacity in this pipeline.

2.5. Effect of inlet pressure

In addition to the pipelines detailed in Table 3, a further set of pipelines was defined to study the effects of inlet pressure on the line-packing time. For this study, the pipeline with the lowest outlet pressure from Table 3 was selected *i.e.* pipeline number 12, which has an OD of 457 mm and a wall thickness of 11 mm wall thickness, with two different flow rates and two different pipeline lengths. For these 6 configurations (detailed in Table 4), the design criteria were slightly different from those described previously. In order to investigate the effect of varying inlet pressure, the outlet pressure from the pipeline was set at 90 bara (pipeline numbers 76–81 in Table 4). The inlet pressure was determined using the hydraulic analysis methodology described in Section 2.3, with a criterion that the inlet pressure must not exceed the MAOP of the pipeline, given by Eq. (3).

3. Line-packing study

3.1. Line-packing methodology

The study of line-packing requires a transient analysis approach in order that the impact of valve closure and the corresponding increase in system pressure with time can be investigated. The transient flow package OLGA (Schlumberger, 2014) was utilised for this study, incorporating the single-component, two-phase (liquid and gas) CO_2 module with the Span and Wagner EOS (De Koeijer et al., 2011; Clausen et al., 2012; Aursand et al., 2013a). OLGA is a two-fluid model, as described by Aursand et al. (2013b), which solves the conservation equations for mass, momentum and energy at discrete time and distance intervals. The numerical procedure utilises the finite difference method such that the pipeline is divided into a number of segments and a solution is sought at the centre of each segment.

At the start of the simulation, stable flow is first established in the pipeline (*i.e.* no variation in inlet or outlet conditions with time) and then the outlet valve is closed. The shutdown time for the valve is assumed to be 5 s (Nimtz et al., 2010). Once the outlet valve is closed, the internal pressure in the pipeline starts to increase. The simulations were stopped at the time when the internal pressure reached the MAOP for the pipeline. This time is defined as the line-packing time in this paper.

The calculated line-packing time is dependent on the choice of segmentation length of the pipeline and the numerical time step. In this study, the discretisation of the solution domain has been conducted with a segment length of 1.3m. At this resolution, the sensitivity of the line-packing time to the discretisation length was calculated to be less than 1%. The time step is limited by the Courant-Friedrichs-Lewy (CFL) condition, $C = U\Delta x/\Delta t$, where C is the Courant number, U is flow velocity, Δx is the width of the pipeline segment (1.3m) and Δt is the numerical time step. Courant numbers less than 1 will assure the stability of the numerical solution (Anderson, 1995). Setting the numerical time step to the order of 0.01 s gives Courant numbers ranging from 0.5 to 0.7 for the scenarios studied.

The transient analysis was conducted for each of the 81 pipelines selected in the steady state analysis, using the pipeline dimensions and inlet conditions detailed in Tables 3 and 4.

3.2. Line-packing results

For the scenarios studied, it can be seen that the line-packing time varies between 127 s and 27,718 s (7.7 h) depending on the combination of pipeline dimensions, flow rate and pressure conditions selected. The next sections discuss the simulation results and draw some initial conclusions regarding options for increasing the line-packing time of a CO_2 pipeline based on simple regression techniques. The results of the regression analysis are presented, however, using these techniques it was not possible to include the influence of all of the variables simultaneously on the line-packing time. Therefore, in order that a comprehensive sensitivity study could be conducted, the ANN tool, described in Section 4, was developed. The specific results from the sensitivity study and the development of the design tool are also

Table 4
Results of steady state and transient analysis for all pipeline designs considered to study the effects of outlet pressure management on line-packing times.

Inlet conditions						Steady state analysis		Transient analysis
						Stress criterion < 72% SMYS	Hydraulic criterion < MAOP	
Pipeline no.	Outer diameter (D_o)/mm	Wall thickness (wt)/mm	Length/km	Flow rate/kg/s	Outlet pressure (P_o)/bara	%SMYS	Inlet pressure (P_o)/bara	Linepacking time/s
76	457	11	50	150	90	45.2	97.9	1746
77	457	11	50	35	90	41.8	90.5	7486
78	457	11	100	150	90	48.7	105.4	2736
79	457	11	100	35	90	42.0	90.9	12,659
80	457	11	150	150	90	52.3	113.3	3310
81	457	11	150	35	90	42.1	91.3	17,640

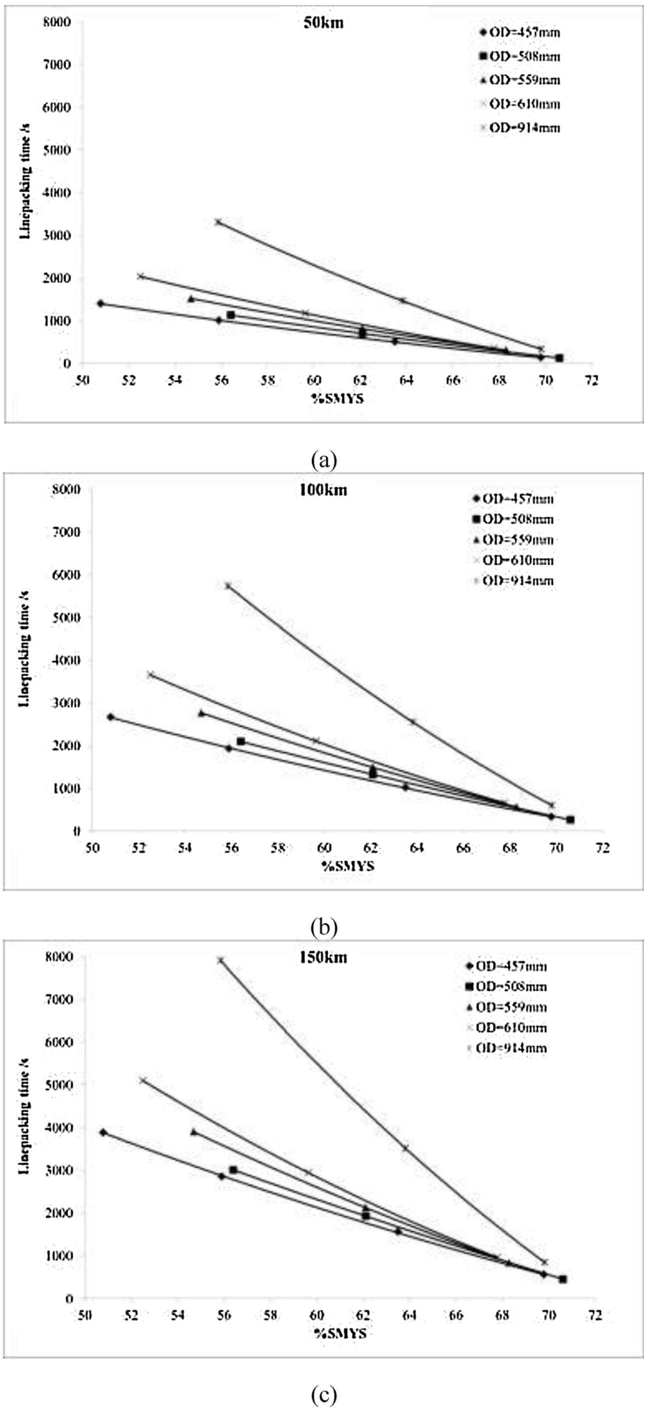


Fig. 2. The effect of stress (%SMYS) on line-packing time for a pipeline carrying 150 kg/s of CO_2 operating at an inlet pressure of 110 bara with given lengths and outer diameters. (a) Pipeline length = 50 km, (b) Pipeline length = 100 km, (c) Pipeline length = 150 km. A second order polynomial trend line (Eq. (6)) has been fitted to the data. The coefficients for the equations are provided in Table 5.

discussed in Section 4.

3.2.1. Impact of pipeline characteristics

Fig. 2 shows how line-packing time varies with %SMYS for a given mass flow rate of 150 kg/s at a constant inlet pressure of 110 bara. Once the outlet valve is closed, the pressure in the pipeline rises from the initial inlet value of 110 bara and approaches the MAOP (calculated at a design stress of 72%SMYS using Eq. (3)). Consequently, Pipelines 22, 23 and 24, which have initial operating stresses of 70.6%SMYS, show the shortest line-packing times. As the %SMYS is reduced (for example, by increasing the wall thickness), the line-packing times increase. The increase is not linear due to the concurrent changes in internal diameter and outlet pressure.

Table 5
Coefficients for the polynomial trendlines shown in Eq. (3) fitted to the data in Fig. 2 to predict the relationship between%SMYS and line-packing time for a pipeline carrying 150 kg/s of CO_2 operating at an inlet pressure of 110 bara.

Pipeline length	OD (mm)	Coefficient a	Coefficient b	Coefficient c	R^2
50 km	914	2.9868	588.19	26842	1.000
	610	1.2989	266.5	12449	1.000
	559	1.1398	229.02	10639	1.000
	508	0.5131	136.07	7175.5	1.000
	457	0.6544	145.32	7092.1	0.999
100 km	914	5.3364	1038.7	47106	1.000
	610	2.5908	507.76	23173	1.000
	559	1.7264	374.43	18080	1.000
	508	0.7021	218.26	12174	1.000
	457	1.2325	270.8	13236	0.999
150 km	914	7.6304	1464.4	65896	1.000
	610	3.8479	733.53	33005	1.000
	559	2.3038	508.51	24822	1.000
	508	1.1153	321.43	17591	1.000
	457	1.5485	360.94	18214	0.998

The relationship between pipeline stress and line-packing time for the conditions modelled can be represented by a second order polynomial of the form:

$$t = a(\%SMYS)^2 + b(\%SMYS) + c \tag{6}$$

where *t* is the line-packing time in seconds (s), *(%SMYS)* is the stress in the pipeline expressed as a percentage of the materials SMYS and *a, b* and *c* are coefficients. This trendline has been fitted to the data in Fig. 2 and the relevant coefficients are provided in Table 5. It is highlighted that these relationships pertain to the particular pipeline input conditions used in the study are presented here for information and comparison.

As would be expected, the largest impact on line-packing times is seen for the longest pipelines at the largest diameters and lowest values of %SMYS, where a decrease in %SMYS of 8% (from 64% to 56% SMYS) can increase the line-packing time by 225%.

3.2.2. Impact of mass flow rate

It would be expected that, as the mass flow rate increases the line-packing time should decrease due to the increased amount of fluid entering the pipeline. Fig. 3 shows the effect of varying mass flow rate on line-packing time for fixed pipeline lengths, outer diameters and wall thicknesses at an inlet pressure of 110 bara. It was found that the relationship between mass flow rate and line-packing time can be fitted to a relationship of the form:

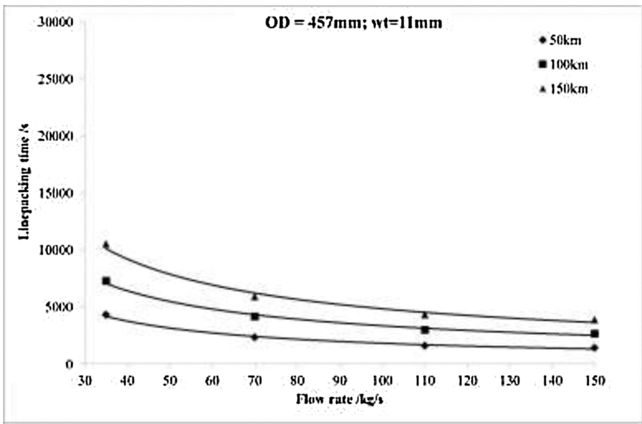
$$t = y \times \dot{m}^{-x} \tag{7}$$

where t is the line-packing time in seconds (s), $\dot{m}$ is the mass flow rate in kg/s, and y and x are coefficients. As shown in Fig. 3, the line-packing time increases with the length of the pipeline and also with the internal area of the pipeline. Therefore relationships were sought between the internal volume of the pipeline and the coefficients y and x by using non-linear regression analysis.

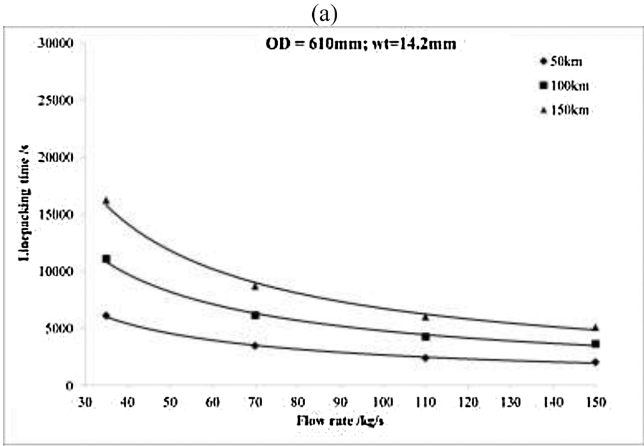
$$y = (2 \times 10^{-5} \times V^2) + (4.3069 \times V) + 29426 \tag{8}$$

$$x = (1 \times 10^{-11} \times V^2) + (6 \times 10^{-7} \times V) + 0.744 \tag{9}$$

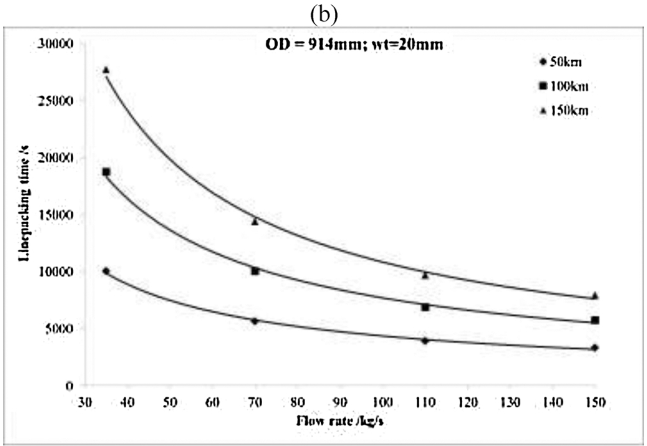
where V is the internal volume of the pipeline in m^3. Along with Eq. (7) it is therefore possible to predict the line-packing time for any particular flow rate. The results of the predictions are presented in Fig. 4. The mean% error of this equation is 9% for the 36 data points in this



(a)



(b)



(c)

Fig. 3. The effect of flow rate on line-packing time for fixed pipeline lengths, outer diameters and wall thickness operating at a constant inlet pressure of 110 bara. (a) OD = 457 mm; wt = 11 mm, (b) OD = 610 mm; wt = 14.3 mm 100 km, (c) = 914 mm; wt = 20 mm. A power law trend line (Eq. (7)) has been fitted to the data.

study.

It is highlighted that the relationships developed in Eqs. (7)–(9) are only applicable to the modelled case studies and the discrete input data used in the study. Consequently it was not possible to conduct a meaningful sensitivity analysis or develop a design tool to predict the line-packing time that covered a range of intermediate input values using these regression techniques. However, the relationships described in Eqs. (7)–(9) do provide useful insight into the possibilities for flexible operation of the pipeline and the timescales available. For example, in the event of an outage at the injection site, such that the downstream

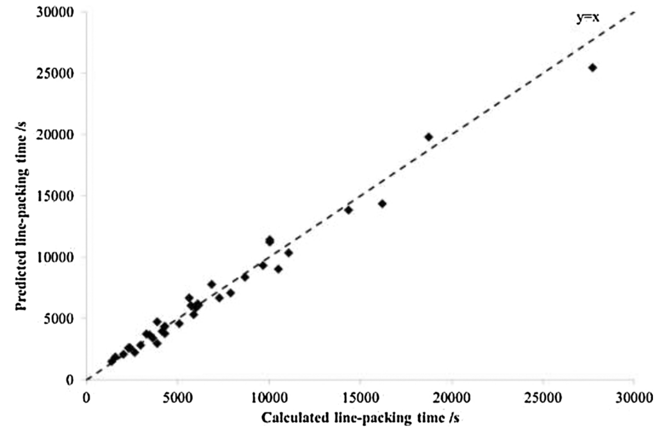


Fig. 4. Relationship between calculated and predicted line-packing times as a function of pipeline internal volume and mass flow rate at a constant inlet pressure of 150 bara. The y = x line indicates the position where the calculated and predicted values would be equal.

valve had to be closed, such relationships would enable a pipeline operator to reduce the flow rate to a level commensurate with the expected timescales to resolve the issue. Specifically, for the 150 km pipeline shown in Fig. 4c, reducing the flow rate could achieve a line-pack time of 5 h which could mean that the operator can avoid having to shut-in the pipeline.

3.2.3. Impact of outlet pressure management

The effect of changing the outlet pressure of the pipeline on line-packing time was also investigated. The results of this analysis are presented in Table 4. If these are combined with other relevant and comparative simulations from Pipelines 10–12 and 19–21, which were all conducted at an inlet pressure of 110 bara, then the line-packing flexibility due to changes in pressure management can be studied. To illustrate this effect, the results for a 457 mm OD pipeline with a wall thickness of 11 mm, are plotted in Fig. 5 for a range of pipeline lengths, mass flow rates and pressures. From this figure, it can be seen that the biggest effect of changing the pressure at the inlet and outlet is observed at lower flow rates. At the lower flow rates, changing the outlet pressure condition increases the line-packing time by approximately 70% for all pipeline lengths. If a combined strategy of managing the outlet pressure and lowering the flow rate is possible then the line-packing times can be increased by factors of up to five times depending on pipeline length (i.e. the relative difference between the shortest and longest line-packing times).

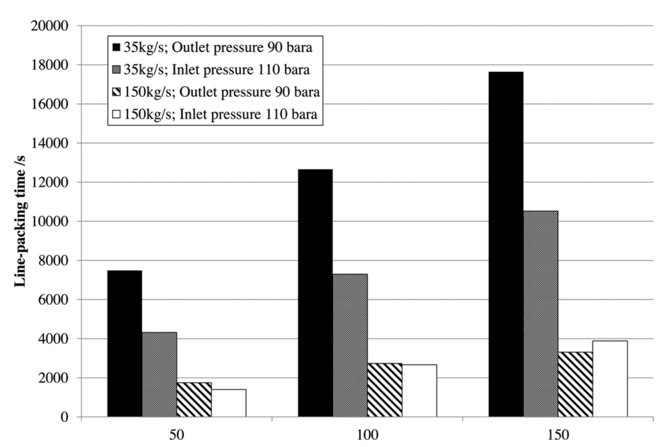


Fig. 5. Effect of changes in flow rate and inlet and outlet pressure management on the line-packing time for a 457 mm OD, 11 mm wall thickness pipeline.

4. Development of an artifical neural network for line-packing time predictions

4.1. ANN methodology

Although the previous analysis indicates that individual relationships could be identified between key input parameters, the integration of all the significant input parameters could not be achieved using simple regression analysis techniques. In particular, as a result of the methodology adopted for this study, it was not possible to separate out the effects of individual variables *e.g.* changing the wall thickness of the pipeline will change the operating stress (through Eq. (1)) but will also change the internal diameter of the pipeline (as the outer diameter remains constant) and therefore the hydraulic characteristics. In order to achieve one of the aims of this work and develop a relationship between the pipeline geometrical and operational characteristics and the line-packing time, an Artificial Neural Network (ANN) has been developed.

An ANN is a statistical machine learning methodology that performs multifactorial analysis on a series of inputs to predict an output. ANNs find particular application in the analysis of problems that have a large number of inputs with a complex relationship to each other and the output. As with other artificial learning methodologies, ANNs 'learn' to weight connections between inputs and output by being presented with a training dataset. Once the ANN has been trained and tested, it can be used to predict an output given a set of input data within the range of the training data set. The function of the ANN developed in this work was to predict line-packing time for a CO_2 pipeline, given information about the size and operating conditions of the pipeline.

The ANN model is constructed from several layers of neurons; an input layer, hidden layer(s) and an output layer. In the context of the ANN being developed for the prediction of line-packing time, the input layer contains the information about the pipeline dimensions, flow rate and inlet and outlet pressure conditions. The output layer is the predicted line-packing time. The number of hidden layers determines the complexity of the network and has a significant influence on the performance of the network. Every neuron in the layer is connected to every neuron in the next layer and the inputs are weighted to give precedence to some inputs over others. The more weight that is given to a particular input the more effect that input has on the overall output of the neural network. An activation function is applied to the sum of the weighted inputs to get the desired output. This architecture is represented schematically in Fig. 6 in which connections with higher weights are represented with bolder lines. The weights are determined through training of the network with a proportion of the dataset. The relationship between the inputs, x_j, where j varies from 1 to N and N is the number of neurons in layer j, and the output, y_p, of an individual neuron at layer p, where $p = j + 1$, can be expressed as:

$$y_p = \varphi\left(\sum_{j=1}^{N} w_{pj}x_j + b_p\right) \tag{10}$$

where w_{pj} is the respective weight of neuron p from neuron j (shown with w in Fig. 6) b_p is the bias and $\varphi(w,x,b)$ is the activation function. A bias can be applied to the input signal to ensure that the output from the network represent known trends and experience. For example, for this application, the line-packing time cannot be negative. It is the matrix of weights and the transfer function for each layer that determines the relationship between the input vector and output vector.

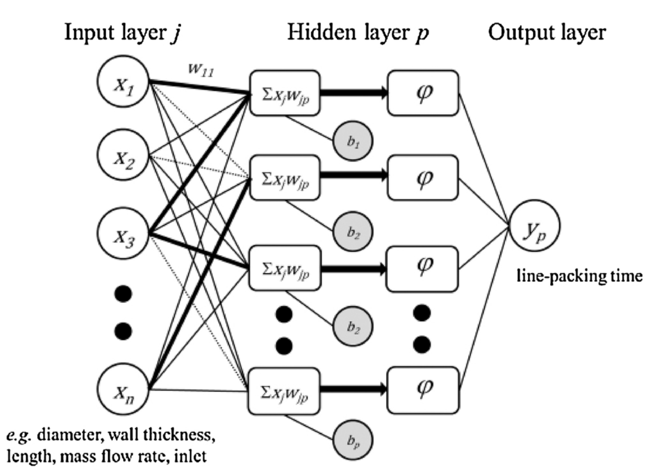


Fig. 6. Schematic of a typical ANN architecture.

4.2. ANN development

The results analysis described in Section 3.2 indicates that the relationship between the input parameters and the line-packing time is non-linear. Therefore, a feed forward, multi-layer network with one hidden layer was chosen for this application because the architecture of this type of network allows the non-linearity of the relationship between inputs and outputs to be taken into account. The log-sigmoid transfer function was selected for the network as it is commonly used in multilayer networks (Hagan, 1996). The transfer function is applied to the input data to produce an output result which is similar to the output data produced in the dataset from the OLGA simulations.

The weights and biases in the model were determined iteratively in order to achieve the optimum performance of the network. Network performance was measured by calculating the mean-squared error (MSE) and coefficient of correlation (R value) of the output predictions. The target was to achieve an MSE close to zero and an R value close to one to attain the most accurate predictions from the model. Initially random, arbitrary values were assigned to the weights and biases. These initial values were then updated using a training algorithm to minimise the MSE and maximise the R value. The training algorithm selected was the Levenberg-Marquardt (LM) back propagation algorithm (MathWorks, 2017). The Bayesian training algorithm was also tested and gave comparable results, however, the LM algorithm was chosen due to its faster computational speed and broader acceptance in the literature (MathWorks, 2017). The number of neurons in the hidden layer was also determined for each network to give the lowest MSE. The optimum number of neurons in the hidden layer was found to be between 10 and 15, for all networks tested.

For this work, the neural network toolbox in MATLAB was used to create, train and optimise a customised ANN model. The dataset of 81 pipelines (Tables 3 and 4) was divided into three subsets using a random data division function in MATLAB – 70% of the data was used for training, 15% for validation, and 15% for testing.

In order to determine the sensitivity of the ANN model to the number of neurons in the input layer, two ANNs were developed with different input data sets. The details of the input data sets are provided in Table 6. ANN1 uses all of the design parameters considered in this study *i.e.* inlet and outlet pressure, OD, wall thickness, pipeline length

Table 6
Input data sets used for the development of ANN1 and ANN2. The MSE is the lowest value that was obtained for the 10,000 networks trained with the validation data.

	ANN1	ANN2
Outer diameter, D_o	x	x
Wall thickness, wt	x	x
Length, L	x	x
Mass flow rate, $\dot{m}$	x	x
Inlet pressure, P_i	x	x
Outlet pressure, P_o	x	
MSE ($\times 10^{-5}$)	0.08	2.53

and mass flow rate. However, in order to develop the input data set for this ANN, a steady-state hydraulic analysis would need to be conducted for every pipeline under consideration to calculate the outlet pressure. Although it would be expected that this network would be more accurate, it is of less practical use when using the ANN as a design tool. Consequently a second ANN (ANN2) was also built in which the outlet pressure is not required as an input parameter. For each ANN (*i.e.* ANN1 and ANN2) 10,000 networks were created and trained to eliminate the randomness caused by the selection of initial weights and biases. Of the 10,000 networks, the network having the lowest MSE and the highest R value for the validation data set was then saved as the final version. The MSE results for the saved versions of ANN1 and ANN2 are shown in Table 6. From these results it can be seen that, as expected, ANN1 gives the least error in the predicted line-packing time when compared against the results of the OLGA analysis.

However, the analysis indicates that the difference between the MSE results for the two networks is very small in real terms and therefore it is considered that ANN2 can also be used as a more versatile preliminary design tool.

4.3. ANN results

4.3.1. Sensitivity analysis

To conduct a sensitivity analysis of the line-packing time to changes in the input variables, noise was added to the input data by adding a randomly generated normal distribution to each set of input data. The mean of the input distribution was taken to be 0.2% of the average of each input and the standard deviation was fixed at 0.5 to ensure that the input data was still physically coherent *i.e.* no negative pipeline dimensions were generated. The predictions of the ANN models using the 'noisy' data as input were compared against those generated using the standard input data for the 81 pipelines detailed in Tables 3 and 4. In order to determine the importance of the variables, the mean squared errors between the noisy and original predictions were compared for each input variable; the higher the MSE, the higher the sensitivity of the line-packing time to that variable. The results are shown in Table 7, which indicates that the wall thickness has the largest effect on line-packing time, followed by the inlet pressure, and that all other inputs have similar secondary effects. The influence of the wall thickness is primarily dominated by the fact that higher wall thicknesses allow operation at higher values of MAOP, which is more significant than the negative effect caused by the reduction in volume caused by increasing wall thickness.

4.3.2. Case study scenario

In order to demonstrate the application of the ANN model as a design tool for line-packing analysis, a case study scenario is presented. The aim of this case study is to illustrate the effect of implementing different design and operational strategies on the line-packing time available if a problem were to occur in the network that required the pipeline to be line-packed. The ANN tool provides a quick and efficient method for the pipeline designer to investigate different options and the benefits that could be accrued in increasing the linepacking time by implementing these changes.

Table 7
MSE values from the sensitivity analysis using ANN1 and ANN2 to determine the variables that had the most significant effect on line-packing time.

	ANN1	ANN2
Inlet pressure, P_i	0.0073	0.0022
Mass flow rate, $\dot{m}$	0.0004	0.0004
Outer diameter, D_o	0.0002	0.0002
Wall thickness, wt	0.1174	0.1185
Length, L	0.0001	0.0001
Outlet pressure, P_o	0.0002	

Table 8
Predictions of line-packing time for a case study pipeline (OD = 914 mm, Inlet pressure = 110 bar, steel grade = Grade EN10208 L450) using ANN2 at two different wall thicknesses.

Wall thickness = 16 mm		Wall thickness = 20 mm	
Mass flow rate (kg/s)	Estimated line-packing time (h)	Mass flow rate (kg/s)	Estimated line-packing time (h)
16.25	5.37	16.25	5.99
32.5	3.64	32.5	4.46
48.75	2.21	48.75	3.37
65	1.26	65	2.60
97.5	0.36	97.5	1.78
130	0.27	130	1.58

The pipeline considered is an 80 km, Grade EN10208 L450 pipeline with an outside diameter of 914 mm. In this scenario, the pipeline has been designed with a maximum stress of 70% SMYS by setting the pipeline wall thickness to 16 mm. Consequently there is a small amount of capacity available to increase the stress in the pipeline to the maximum allowable stress of 72%SMYS. The baseline mass flow rate into the pipeline is 2Mt/year (65 kg/s) and the inlet pressure is 110 bar. It is highlighted that linepacking times for this pipeline have not been calculated using a transient hydraulic analysis but the input data lies within the range of data used to train the ANN. ANN2 was chosen to conduct the further analysis in the case study as this network does not require a static hydraulic analysis to be conducted in order to calculate the outlet pressure as an input variable to the network.

As discussed in Section 3.2.2, one of the options open to the operator is to reduce the flow rate into the pipeline when the outlet valve is closed. Consequently, the flow rate into the pipeline was changed to values between −75% and +100% of the baseline flow rate (65 kg/s). Table 8 shows the predictions from the ANN for this pipeline for changes in flow rate. It can be seen that for this scenario, a line-packing time of between 0.3 and 5.4 h could be achieved in the pipeline through manipulation of the flow rate. However, consider now the case where an operator includes line-packing as a design parameter and increases the wall thickness of the pipeline by 20% to 20 mm. The operating stress for this pipeline is 56%SMYS. The results in Table 8 show that, at the baseline flow rate, the line-packing time can be doubled by changing the wall thickness by 20%. The difference is even higher at higher flow rates, although not as marked at lower flow rates. Using the ANN as a design tool in this way allows the pipeline operator to make decisions on the benefits of variation in input values at the design stage.

Through this case study, it has been that an ANN can provide a convenient tool for pipeline designers to use when considering the effect of different parameters during the preliminary design phase of a CO_2 pipeline. It would be possible to link the ANN to a pipeline techno-economic model, which would enable the benefit of various design options on both the capital cost and operational costs of the pipeline to be quantified, taking into account the concomitant cost penalties for venting and system downtimes.

It is highlighted that, once the design has been finalised, it is always recommended that a full static and transient hydraulic analysis is undertaken using appropriate hydraulic simulation software in order that line-packing times can be accurately determined.

5. Discussion and conclusions

One of the main conclusions of this work is that, whilst line-packing time can be increased during operation of the pipeline, through the modification of the mass flow rates and inlet pressures, the ability of the pipeline to act as a short-term storage option within the network should also be considered at the pipeline design stage. In this paper, it has been demonstrated that, as would be expected, the line-packing capacity of the pipeline can be increased by increasing the available internal

Table 9
Range of validity of key parameters for the ANN.

	Unit	Range of validity
Outer diameter, D_o	mm	457–914
Wall thickness, *wt*	mm	8–20
SMYS	%	50.8–70.6
Length, L	km	50–150
Mass flow rate, $\dot{m}$	kg/s	35–150
Inlet pressure, P_i	bara	90.5–113
Inlet pressure, P_o	bara	87–110

volume of the pipeline, reducing the mass flow rate into the pipeline, increasing the allowable operating stress and managing the inlet pressure and outlet pressures. This work has indicated that, for pipeline dimensions typical of those considered for CCS schemes, line-packing times of upto 8 h would be feasible for dense phase CO_2 pipelines. Whilst this could be useful as a short term storage option, which may allow operational issues elsewhere in the network to be addressed, it will not provide a solution to a major planned or unplanned outage at the capture or injection site. However, it may allow for short-term maintenance activities (*e.g.* at compressor and pump stations) to be undertaken whilst maintaining the output from the capture plant.

If flexibility of the pipeline system is considered at the design phase then the capacity for line-packing could be increased. This work has demonstrated that, for the input data considered, the variable that has the most impact on the line-packing capacity of a pipeline is the wall thickness. Although increasing the wall thickness reduces the internal volume of the pipeline, for a given fixed outside diameter, the effect that the wall thickness has on increasing the allowable stress in the pipeline outweighs this effect. The selection of wall thickness obviously has to be considered at the design stage and will have a concomitant impact on the cost of the pipeline and the inlet and outlet pressure. In pipeline design, the wall thickness is generally selected to satisfy stress based design criterion, although for CO_2 pipelines containing impurities, in particular, it has been shown that increasing the wall thickness of the pipe is a key factor in controlling fracture propagation (Race et al., 2012). This work has shown that the effect of line-packing should also be considered at the design stage if the flexibility of the network is a key consideration.

It has been shown that the relationships between the key variables in determining the line-packing time are inter-related and non-linear. Consequently, it was found that the most appropriate method for investigating the effects of input variables on the line-packing time was through a multi-variate analysis or machine learning methodology, such as ANNs. Through this work, it has been demonstrated that an ANN can be used to develop a tool for evaluation of the available options for increasing the line-packing times for a CO_2 pipeline. However, as with all statistical analytical tools, using the ANN outside of the bounds of the data on which it has been trained can lead to uncertain results. Therefore, the tool is only recommended for pipelines carrying pure CO_2 on flat terrain and within the data limits for the variables shown in Table 9.

The dataset developed for this work has been derived through a detailed process of static and hydraulic analysis to ensure that constraints on stress design and hydraulic performance are maintained. However, it is recommended that when finalising a pipeline design, a static analysis is conducted to ensure that the stress based and hydraulic design criteria are both met for the pipeline input conditions selected.

Acknowledgements

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References

Anderson, J., 1995. Computational Fluid Dynamics. McGraw-Hill.

Aursand, E., Aursand, P., Berstad, T., Dorum, C., Hammer, M., Munkejord, S.T., Nordhagen, H.O., 2013a. CO_2 pipeline integrity: a coupled fluid-structure model using a reference equation of state for CO_2. Energy Procedia 37, 3113–3122.

Aursand, P., Hammer, M., Munkejord, S.T., Wilhelmsen, O., 2013b. Pipeline transport of CO_2 mixtures: models for transient simulation. Int. J. Greenh. Gas Control 15, 174–185.

Carter, R.G., Rachford Jr., H.H., 2003. Optimizing line-pack management to hedge against future load uncertaininty. In: Proceedings of the 35th PSIG Annual Meeting. Bern, Switzerland. paper 0306.

Clausen, S., Oosterkamp, A., Strom, K.L., 2012. Depressurization of a 50 km long 24 inches CO_2 pipeline. Energy Procedia 23, 256–265.

Cosham, A., Jones, D.G., Armstrong, K., Allason, D., Barnett, J., 2012. The decompression behaviour of carbon dioxide in the dense phase. In: 9th International Pipeline Conference, IPC 2012. Calgary, AB. pp. 447–464.

De Koeijer, G., Borch, H.J., Drescher, M., Li, H., Li, H., Wilhelmsen, Ø., 2011. CO_2 transport–depressurization, heat transfer and impurities. Energy Procedia 4, 3008–3015.

EN ISO 3183, 2012. Petroleum and Natural Gas Industries – Steel Pipe for Pipeline Transportation Systems (ISO 3183:2012). CEN European Committee for Standardisation.

Hagan, M.T., 1996. Neural Network Design, 1st ed. PWS Pub., Boston.

IEAGHG, 2013. UK FEED studies 2011- a summary, 2013/12, October 2013.

ISO 4200, 1991. Plain End Steel Tubes, Welded and Seamless – General Tables of Dimensions and Masses Per Unit Length. International Standards Organisation, Geneva, Switzerland.

Klinkby, L., Nielsen, C.M.L., Krogh, E., Smith, I.E., Palm, B., Bernstone, C., 2011. Simulating rapidly fluctuating CO_2 flow into the Vedsted CO_2 pipeline:injection well and reservoir. Energy Procedia 4, 4291–4298.

Kreith, F., Bohn, M.S., 2001. Principles of Heat Transfer, 6th ed. Brooks Cole.

Krishnaswami, P., Chapman, K.S., Abbaspour, M., 2004. Compressor station optimization for line-pack maintenance. In: Proceedings of the 36th PSIG Annual Meeting. Palm Springs.

MathWorks, 2017. Artificial Neural Network Toolbox User's Guide. The Math Works Inc.. http://www.mathworks.com. (Accessed 21 February 2017).

Mohitpour, M., Golshan, H., Murray, A., 2007. Pipeline Design and Construction, 3rd ed. ASME Publication, USA.

NIST, 2007. Thermophysical Properties of Hydrocarbon Mixtures Database (SUPERTRAPP). National Institute of Standards and Technology Version 3.2 ed.

Nimtz, M., Klatt, M., Wiese, B., Kuhn, M., Krautz, J.H., 2010. Modelling of the CO_2 process- and transport chain in CCS systems—examination of transport and storage processes. Chem. Erde – Geochem. 70, 185–192.

PD8010-1, 2015. Code of Practice for Pipelines, Part 1: Steel Pipelines on Land. British Standard Institution.

Pedersen, K.S., Fredenslund, A., Christensen, P.L., Thomassen, P., 1984. Viscosity of crude oils. Chem. Eng. Sci. 39, 5.

Race, J.M., Seevam, P., Downie, M.J., 2007. Challenges for offshore transport of anthropogenic carbon dioxide. In: 26th International Conference on Offshore Mechanics and Arctic Engineering, OMAE 2007. San Diego, California, USA : ASME.

Race, J.M., Wetenhall, B., Seevam, P.N., Downie, M.J., 2012. Towards a CO_2 pipeline specification: defining tolerance limits for impurities. J. Pipeline Eng. 11 (3), 173.

Rios-Mercado, R.M., Borras-Sanchez, C., 2015. Optimization problems in natural gas transportation systems: a state-of-are review. Appl. Energy 147, 536–555.

Sanchez Fernandez, E., Goetheer, E.L.V., Manzolini, G., Machhi, E., Rezvani, S., Vlugt, T.J.H., 2014. Thermodynamic assessment of amine based CO2 capture technologies in power plants based on European Benchmarking Task Force methodology. Fuel 129, 318–329.

Sanchez Fernandez, E., Sanchez del Rio, M., Chalmers, H., Khakharia, P., Goetheer, E.L.V., Gibbins, J., Lucquiaud, M., 2016a. Operational flexibility options in power plants with integrated post-combustion capture. Int. J. Greenh. Gas Control 48, 275–289.

Sanchez Fernandez, E., Naylor, M., Lucquiaud, M., Wetenhall, B., Aghajani, H., Race, J., Chalmers, H., 2016b. Impacts of geological store uncertainties on the design and operation of flexible CCS offshore pipeline infrastructure. Int. J. Greenh. Gas Control 52, 139–154.

Schlumberger, 2012. PIPESIM software version, 2012.1.

Schlumberger, 2014. OLGA software version, 7.3.4.

Seevam, P., 2010. Transporting the Next Generation of CO_2 for Carbon Capture and Storage Ph.D. Newcastle University.

Span, R., Wagner, W., 1996. A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. J.

Phys. Chem. Ref. Data 25, 1509–1596.
Uilenreef, J., Kombrink, M., 2013. Flow Assurance & Control Philosophy ROAD – Special Report for the Global Carbon Capture and Storage Institute.
Vandeginste, V., Piessens, K., 2008. Pipeline design for a least-cost router application for CO_2 transport in the CO2 sequestration cycle. Int. J. Greenh. Gas Control 2, 571–581.
Wetenhall, B., Race, J.M., Downie, M., 2014a. The effect of CO_2 purity on the development of pipeline networks for carbon capture and storage schemes. Int. J. Greenh. Gas Control 30, 197–211.
Wetenhall, B., Aghajani, H., Chalmers, H., Benson, S.D., Ferrari, M.-C., Li, J., Race, J.M., Singh, P., Davison, J., 2014b. Impact of impurity on CO_2 compression, liquefaction and transportation. Energy Procedia 63, 2764–2778.
Wiese, B., Nimtz, M., Klatt, M., Kuhn, M., 2010. Sensitivities of injection rates for single well CO_2 injection into saline aquifers. Chem. Erde – Geochem. 70, 165–172.