International Journal of Greenhouse Gas Control 63 (2017) 86–94

Contents lists available at ScienceDirect

International Journal of Greenhouse Gas Control

journal homepage: www.elsevier.com/locate/ijggc

The main factors affecting heat transfer along dense phase CO_2 pipelines

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ARTICLE INFO

Keywords:
CO_2 pipelines
Temperature profile
Sensitivity analysis
Heat transfer
Soil temperature
Hydraulic modelling
CCS

ABSTRACT

Carbon capture and storage (CCS) schemes will necessarily involve the transportation of large volumes of carbon dioxide (CO_2) from the capture source of the CO_2 to the storage or utilisation site. It is likely that the majority of the onshore transportation of CO_2 will be through buried pipelines. Although onshore CO_2 pipelines have been operational in the United States of America for over 40 years, the design of CO_2 pipelines for CCS systems still presents some challenges when compared with the design of natural gas pipelines. The aim of this paper is to investigate the phenomenon of heat transfer from a buried CO_2 pipeline to the surrounding soil and to identify the key parameters that influence the resultant soil temperature. It is demonstrated that, unlike natural gas pipelines, the CO_2 in the pipeline retains its heat for longer distances resulting in the potential to increase the ambient soil temperature and influence environmental factors such as crop germination and water content. The parameters that have the greatest effect on heat transfer are shown to be the inlet temperature and flow rate, i.e. pipeline design parameters which can be dictated by the capture plant and pipeline's design and operation rather than environmental parameters. Consequently, by carefully controlling the design parameters of the pipeline it is possible to control the heat transfer to the soil and the temperature drop along the pipeline.

1. Introduction

Carbon capture and storage (CCS) is one method of reducing carbon dioxide (CO_2) emissions into the atmosphere which would otherwise contribute towards global climate change. CCS involves capturing CO_2 from a large industrial point source (such as a power station) and transporting the CO_2 for either usage (for example for enhanced oil recovery (EOR)) or for permanent storage in a geological site. Depending on the distance and availability of a suitable storage site, the transportation of the CO_2 to the storage site is by means of a pipeline network, by ship based transportation or a combination of both.

For the onshore pipeline transportation of CO_2, after compression at the capture plant, the CO_2 streams will typically be at temperatures between 30 °C and 50 °C and pressures between 10 MPa and 20 MPa (Farris, 1983; Race et al., 2012) putting the CO_2 streams in either supercritical or dense phase. For CO_2 pipelines, it is important to understand how the temperature of the fluid varies along the pipeline, as the temperature determines the phase of the fluid and affects density, pressure drop (Dongjie et al., 2012) and economics (Teh et al., 2015; Zhang et al., 2006). Colder ground conditions provide greater cooling of the CO_2 stream and, as a result, lower inlet pressures are required to keep the CO_2 in a liquid phase. In addition, higher densities are maintained at lower temperatures, which is more efficient for pipeline transportation and better for pump operation.

When the fluid temperature is higher than that of the surrounding soil, due to the temperature difference between the CO_2 and surroundings and elevation changes along the pipeline route, there will be heat exchange between the CO_2 stream and the surrounding environment with the temperature of the fluid getting closer to (but not necessarily reaching) ambient temperature along the length of the pipeline. The heat transfer between the fluid and the surrounding soil takes place in 4 stages: firstly there is forced convection from the film of fluid coating the inner surface of the pipeline, the second stage of heat transfer is conduction through the pipe wall, heat transfer then proceeds via conduction from the outer surface of the pipeline and through the surrounding soil. Finally there is natural convection from the surface of the soil to the surrounding air. In the conduction stages through the pipeline and from the pipeline to the soil, it is possible to include the effects of any pipeline coatings (which may be included on the pipe internal surface, for example to, facilitate flow) and insulation on the outside of the pipe. In this work coatings are neglected due to a lack of publically available information on their heat transfer properties and no insulation is added to the pipeline following the planned demonstration

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http://dx.doi.org/10.1016/j.ijggc.2017.05.003
Received 23 November 2016; Received in revised form 3 March 2017; Accepted 7 May 2017

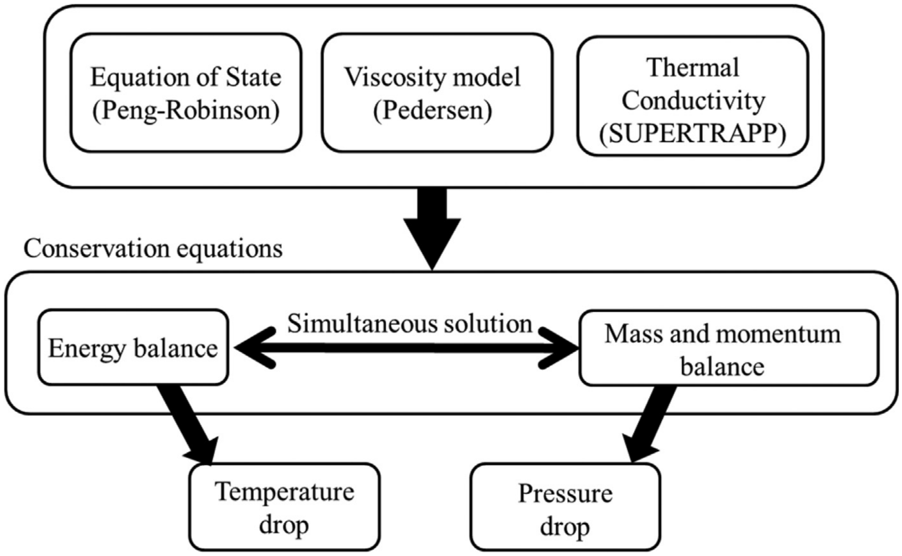

Fig. 1. Flow diagram indicating the calculation methodology in the hydraulic analysis.

projects in the UK (Capture Power, 2016).

In natural gas pipelines the fluid generally reaches ambient temperature very rapidly but in CO_2 pipelines this process can be much slower. Heat transfer from the fluid to the surroundings can cause environmental issues. For example, pipelines carrying warm fluid can cause heating of the surrounding soil, which may result in premature crop growth and affect soil moisture and the temperature along the pipeline right of way (ROW) (Dunn et al., 2008; Naeth et al., 1993; Neilsen et al., 1990) in some circumstances. In order for a pipeline operator to be able to manage these effects, it is important to understand the degree of influence that operational and environmental factors have on heat flux from the fluid to the surrounding soil. Factors influencing the degree of heat flux from a buried pipeline include the fluid pressure and temperature, the soil temperature, the soil type and moisture content (Becker et al., 1992), the thermal conductivity of the pipeline steel and the elevation profile along the pipeline route (Teh et al., 2015). Some parameters such as the temperature of the fluid, operating pressure and initial temperature of the CO_2 can be controlled at the capture plant. Other parameters, such as the soil type and ambient temperature are out of the control of the pipeline operator.

1.1. Heat transfer from CO_2 pipelines

There is very little publically available work on heat transfer from CO_2 pipelines. The heat transfer characteristics of CO_2 pipelines surrounded by water were analysed experimentally and computationally by Drescher et al. (2013). They found that the water temperature has a high impact on the amount of heat transfer and a range of values for the overall heat transfer coefficient for a CO_2 pipelines surrounded by water, finding a mean value of 44.7 W/m^2 K. The importance to CO_2 pipeline operation of the soil temperature and type, thermal conductivity of the pipeline and topography of the pipeline route was highlighted in Dongjie et al. (2012) and Teh et al. (2015). They found that transporting and storing liquid CO_2 can be cheaper than supercrtical CO_2, that cooler ground conditions can lead to cost savings and highlighted the need for futher work to explore the effect of burial depth and of soil thermal conductivity. The effect of pipeline operating temperature on UK soils was investigated in Lake et al. (2016) who provided the first set of empirical data on soil temperature and moisture profiles for CCS pipelines. There is still need for further work on how best to operate a CO_2 pipeline with regards to heat transfer and experimental work into heat transfer from full scale CO_2 pipelines. This work is a step towards the former.

Through pipeline simulations and a sensitivity analysis this study identifies the dominant parameters affecting heat transfer from liquid CO_2 pipelines and discusses how an operator can control heat transfer out of the pipeline to minimise the impact of heat transfer. Firstly a preliminary study was conducted consisting of a series of eight steady-state pipeline simulations. This allowed an investigation of the influence of ground temperature, flow rate, inlet temperature, burial depth, soil conductivity, inlet pressure and CO_2 composition on the rate of temperature loss along the pipeline and a comparison to previous results. A sensitivity analysis, using a Gaussian emulator, was then performed to identify which of the parameters investigated in the preliminary analysis had the strongest influence on the temperature drop along the pipeline. The Gaussian emulation approach is highly computationally efficient (far fewer model runs are required compared with, for example, Monte-Carlo based methods), it allows for a complete range of sensitivity measures to be computed from one set of pipeline simulation results and statistical performance is included in the process. It is applicable to the current study because the data from the pipeline simulations is smooth (i.e. there are no sudden jumps when moving between data points). Smoothness was ensured by keeping the pipeline simulations in the dense or supercritical phase.

2. Hydraulic modelling of the CO_2 pipelines

2.1. Model setup

The modelling approach that was adopted for this study is described in detail in (Wetenhall et al., 2014). Heat transfer modelling details are given in Section 2.2 while the other details are presented in summary. PIPESIM, a steady-state flow simulator (Schlumberger, 2010), was used to conduct the hydraulic modelling of the CO_2 pipeline. As implemented in the software package MultiFlash (Infochem, 2011), the fluid physical (density, enthalpy, compressibility and heat capacity) and phase properties were determined using the Peng–Robinson Equation of State (Peng and Robinson, 1976), fluid viscosity was calculated using the Pedersen model (Pedersen et al., 1984) and SUPERTRAPP (NIST, 2007) was used to determine fluid thermal conductivity. Fig. 1 shows a flow diagram for the pipeline simulation procedure as implemented in PIPESIM. The procedure requires the simultaneous solution of the conservation of mass, momentum and energy equations. From the solution of these equations, the pressure and temperature drops along the length of the pipeline can be calculated given two of the parameters of initial pressure, final pressure or flow rate. It is recognised that the