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The importance of ground temperature to a liquid carbon dioxide pipeline

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ABSTRACT

Considerable research and development has been conducted into vary techniques to capture carbon dioxide (CO_2), including its safe and economical transportation to the storage sites. The CO_2 will normally be compressed to the supercritical phase where it demonstrates properties of both liquid and the gas. An alternative for transportation involves the operation solely in the liquid phase. Transporting supercritical CO_2 will demand a larger pipe size and consumes more compressor power because its fluid density is lower than the density of liquid CO_2. A significant amount of thermal insulation is also required to maintain the phase and contributes additional cost. This paper firstly model and explore the basic difference between transporting supercritical and liquid CO_2, then proposes transporting liquid CO_2 with the complete utilization of heat exchange between the ground and CO_2 fluid.

The pipeline will inevitably face heat exchange between the fluid inside and the surrounding environment due to temperature difference and elevation. In order to avoid phase change, it is necessary to take into account factors such as ambient/soil temperature, soil type, thermal conductivity of pipe and elevation of terrain for ensuring a safe, reliable and cost effective transportation. The models developed in this paper aim to contribute to existing knowledge by highlighting the importance of these factors and laying the foundation for future work when the ambient temperature and elevation changes.

A commercially available simulator Aspen HYSYS® V7.2 in steady state mode, the Peng Robinson Equation of State was used for modelling.

1. Introduction

1.1. Transportation method

CO_2 can be commercially transported as a gas and liquid by pipes, tankers, cargo vessels, barges, trucks or railroad cars. Many studies have stated that large scale implementation of carbon capture and sequestration (CCS) would require a transmission system to efficiently and economically transport CO_2 from the capture site to the permanent storage site. It is then understood that one of the practical ways to transfer dense phase CO_2 (either supercritical fluid or sub-cooled liquid) in large quantity would be a dedicated pipeline network. This is based on the experience which several millions of tonnes of CO_2 have been transported by pipelines mostly for (EOR) enhanced oil recovery fields in United States, Canada and Norway (Lauer 2008).

CO_2 must to be transported in high density if it is in a large amount. Solid CO_2 (dry ice) has a theoretical density of 1500 kg/m^3 however it is believed to be uneconomical due to its complex handling procedures. Zhang et al. (2005) has proposed that transporting gaseous CO_2 is disadvantages due to its low density and results in higher pressure drop and larger pipe diameter. However, (Knoope et al., 2013) defended that gaseous CO_2 transport may be cost effective if the mass flow rates are relatively small; pressure requirement is less than 80 bar and for short distance. Another attractive way of transportation is by semi-pressurized ship which is similar to the one for transporting liquefied petroleum gas (LPG) and ethylene. Nevertheless ship transportation will consume extra space and extra cost for constructing an intermediate storage before the ship docks, loading and unloading system. Hence, this paper is written in the context of transporting a large amount of CO_2 from a single source, such as the CO_2 captured from a coal fired power plant by cryogenic liquefaction, to an onshore injection site using a buried pipeline and at high pressure for the require-

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Table 1
Quick comparison between pipeline transport and ship transport.

Design consideration	Pipeline transportation	Ship transportation
Transport condition of CO_2	Either sub-cooled liquid or supercritical at high pressure	Sub-cooled liquid at low pressure, very close to triple point of CO_2
Requirement of re-liquefaction facilities as safety precaution	In cold climate if above/below ground, no In warm climate if above ground, yes	On board liquefaction facilities for boil up
The location of injection site preferred	Both on-shore and offshore	Offshore Onshore unless crossing countries
Maturity of technology	Mature and the pipeline design is very similar to the one for natural gas (Parfomak et al., 2009)	Not yet mature therefore using the similar technology for LPG and ethylene (Aspelund et al., 2006)
Codes and standards	ASME standards B31.4 and B31.8 (B31.8s), IP6, BS EN 14161, BS PD 8010, ISO13623 and DNV OS-F101	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, also known as IGC Code (Kokubun et al., 2013)

ment of storage/sequestration site. A quick comparison between the pipeline transportation and ship transportation of CO_2 is provided in Table 1 below:

1.2. Pipeline performance model

The optimization of the pipeline cost model requires the determination of the optimum pipeline diameter and to obtain that, it involves the development of pipeline performance model. The pipeline performance model developed by (McCoy Sean, 2008) consists of several basic design parameters such as the fluid density, fluid viscosity, Reynolds number (RE), friction factor, pipe diameter and equivalent length. In terms of cost models, Knoope et al. (2013) identified several types of cost models exist in literature such as the linear models, models based on the weight of the pipeline, quadratic equations and CMU model and each model has their own limitations. For techno-economic evaluations, (Luo et al., 2014) uses Aspen HYSYS®ⁱntegrated with Aspen Process Economic Analyser®.

1.3. Heat transfer aspect of CO_2 pipeline

When the CO_2 flows along the pipeline, the fluid will be inevitably influenced by the shear/friction force between the fluid and pipe wall (as a result of viscous nature of real fluid), the heat exchange between the fluid and surrounding soil (due to temperature difference) and any change in elevation. Zhang et al. (2005) simulated two CO_2 transport scheme using identical pipe diameter for comparison, one is supercritical state transport and one is subcooled liquid transport, and concluded that subcooled liquid transport is more economical and can be more feasible in areas with cold climate. A hydrodynamic model results given by Zhang et al. (2011) also show that soil temperature and elevation change have significant impact on pressure drop. Consequently, the objective of this paper is to further strengthen these concepts proposed by Zhang et al. (2005) by modelling a buried pipeline for both liquid and supercritical CO_2 under two different climates, one is cold climate with ambient temperature of 20 °C and another one is warm climate with ambient temperature of 40 °C, as shown in Fig. 2.

For a steady state operation, the CO_2 fluid temperature can decrease or increase as it flows through the pipeline and Zhang et al. (2005) defined this significant exchange of thermal energy as isothermal condition and claimed that the transmission distance will be shorter than the one for adiabatic condition. Due to the incompressible nature of liquid, the difference between adiabatic and isothermal is insignificant. The heat transfer characteristics of the pipeline such as the flow regime and the physical properties of the surrounding medium will govern the rate of cooling/heating (Drescher et al., 2013). Considering the case which CO_2 fluid is hotter than the ambient temperature, the heat transfer process should be dissected into four steps:

Step 1: Forced convection from the CO_2 fluid to pipe wall due to pumping action. Depending on the type of correlation used, the heat transfer coefficient value (the 'h' in Eq. (1)) is generally a function of two dimensionless numbers such as Reynolds number (a function of fluid velocity, viscosity and hydraulic diameter of pipe) and Prandtl number (a function of specific heat, dynamic viscosity and thermal conductivity of fluid).

For convection, Newton's law of cooling shown in Eq. (1)) is used, where h is the heat transfer coefficient of CO_2 fluid (W/m^2K), T_s is the surface temperature of inner pipe wall and T∞ is the temperature of the CO_2 fluid in the middle of pipe.

$$q = h(Ts - T\infty) \tag{1}$$

Step 2: Conduction across the pipe wall to the soil adjacent to the pipe wall (Eq. (2)).

Fourier's law states that the transfer of energy ($q_{\text{conduction}}$) through the pipe wall via conduction is directly proportional to the driving force i.e. the temperature gradient (rate of change of temperature with respect to x) where k is the conductivity of the pipe wall (W/mK). The negative sign indicates that the heat is transferred in the direction of decreasing temperature.

$$q = -k\frac{dT}{dx} \tag{2}$$

Step 3: Conduction across the soil from the pipe wall to the ground surface, this would require the determination of thermal conductivity of a particular soil type (k_{soil}) and subject to buried depth.

Step 4: Natural convection from the ground surface to the air (the heat transfer coefficient value (h) is governed by local wind speed).

Eq. (1) can be used for convection from the ground surface to the air and Eq. (2) can be used for conduction across the soil. Based on the first law of thermodynamics for conservation of energy, the four q values should be equal ($q_{\text{ConvectionfromCO2fluidtopipewall}} = q_{\text{Conduction-pipewall}} = q_{\text{conduction-soil}} = q_{\text{convectionfromgroundsurfacetoair}}$). By performing an energy balance, the temperatures at the ground surface and the temperature on outer and inner pipe wall can be estimated.

If the ambient temperature is higher than the CO_2 fluid temperature, the heat transfer process will be reversed. For simplifying the modelling process, both convective heat transfers (step 1 and 4) were neglected in this paper because of low velocity CO_2 flow and the lack of information for local wind speed. For conduction across the pipe wall (step 2), pipeline engineers should be aware that in practice pipeline coating will be applied on the pipe surface below insulation (if any) for preventing serious and irrecoverable damage by surface corrosion. In some cases, coating can also be applied on internal surface for the purpose of either flow improvement or corrosion protection and is generally not recommended due to the risk of detachment. DNV standard has highlighted the consideration of the insulation properties of exter-