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Fracture propagation control in CO_2 pipelines: Validation of a coupled fluid–structure model

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ABSTRACT

Existing engineering methods to ensure fracture propagation control in natural-gas transmission pipelines have been shown to be non-applicable when dense-phase CO_2 is transported. To overcome this, a coupled fluid–structure interaction model has been developed. It consists of a homogeneous equilibrium flow model, coupled with the Span–Wagner equation of state and including solid-phase formation, and a finite-element model of the pipe taking into account large deformations and fracture propagation through a local fracture criterion.

Model predictions are compared with data from two medium-scale crack-arrest experiments with dense-phase CO_2. Good agreement is observed in fracture length, fracture-propagation velocity and pressure. Simulations show that, compared to natural-gas pipelines, the pressure level at the opening fracture flaps is sustained at a much higher level and at a much longer distance behind the moving fracture tip. This may be one important reason why the existing engineering methods do not work for dense-phase CO_2.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) [1], there is 95% certainty that human activity is the dominant cause of observed warming since the mid-20th century. Therefore, climate-change-mitigation efforts must increase. In particular, for the electricity production and industry sector, CO_2 capture, transport and storage (CCS) represents an important and, for many scenarios, a necessary mitigation measure for achieving low-stabilization levels of atmospheric CO_2 [2,3].

In the two-degree scenario of the International Energy Agency [2], CCS contributes to a CO_2-emission reduction of about 6 Gt per year in 2050. The storage reservoirs will, in general, not be colocated with the capture facilities. Thus, full-scale deployment of CCS will require large amounts of CO_2 to be transported. A large fraction of this is likely to be done by pipelines. For comparison, consider that the Norwegian natural-gas export is about 110 billion standard cubic metres [4], which is roughly 75 Mt per year. Due to the scale alone, it will be of great importance to design and operate CO_2-transport systems in a safe and efficient way. In addition, CO_2 transport will differ from that of natural gas in several ways [see e.g. 5]. The CO_2 will, in most cases, be transported in a liquid or dense liquid state, whereas the natural gas normally is in a dense gaseous state. This affects the behaviour during depressurization, where CO_2 will undergo phase transition. Also, depending on the capture technology, the level and type of impurities will vary [6], and this may significantly alter the thermophysical properties [7–9].

Several researchers have found that CO_2 pipelines may be more susceptible to long running-ductile fractures (RDF) than e.g. natural-gas pipelines [10–13]. As a result of this, fracture propagation control (FPC) is an issue that requires careful consideration in the design and operation of CO_2 pipelines. An RDF may be triggered e.g. by corrosion or third-party damage to the pipeline. It is governed by the ‘race’ between the depressurization wave in the fluid inside the pipe, and the fracture-propagation velocity. If the depressurization wave is fastest, the pressure at the fracture tip will decrease and the running fracture will arrest. Otherwise the running fracture may continue for a long distance, causing economical and potentially human loss. It is possible, and indeed required, to design the pipelines to avoid RDF for more than 1–2 pipe sections [14]. For a given operating condition, this may be done by selecting tough enough materials, thick enough pipe walls, or by equipping the pipeline with crack arrestors, which are rings fitted to the exterior of the pipe. All these measures have a cost, and it is therefore of interest to estimate accurately how much is required to maintain safety.

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Widespread deployment of CCS will imply that some onshore CO_2-transport pipelines run through or nearby populated areas. Due to the high pipeline pressure and the fact that CO_2 is asphyxiant at high concentrations, safety guidelines and new best-practice manuals will be required. Developing such guidelines demands accurate models for predicting both the risk and evolution of pipeline fractures [15]. Pipelines can then be designed specifically to avoid the significant hazards and financial costs associated with the formation of a long RDF – while reducing the need for safety factors.

1.1. Existing FPC methods for pipelines

Several approaches to predict and understand the RDF problem in pipelines, and thus obtain FPC in pipelines, have been developed over the years (see [16–18] for a more complete review). These approaches to FPC in pipelines can be divided into three classes:

Class 1: semi-empirical methods based on correlations with full-scale experiments e.g. [19–21],
Class 2: energy-balance-based methods e.g. [22,23] and
Class 3: direct (fluid–structure interaction) calculations e.g. [10,24–28].

The first two classes consider the fluid and the structure to be uncoupled, and the resulting computations are not intensive. The energy-based approaches are not widely used for engineering purposes, but might e.g. give important insight into the relative importance of different parameters in the RDF problem, e.g., as done in [22,23]. In the third class of approaches, the fluid and the structure are more or less coupled, and the resulting computations are much more intensive, though in most versions, the fluid-mechanics calculations do not consider the interaction between the opening fracture flaps and the fluid flow.

The engineering methods, represented by the first class above, are the main tool used for handling FPC and RDF problems in pipelines today. These are semi-empirical and have been developed mainly for natural-gas transport and for older steel types [29]. Such models need (at best) re-calibration when applied to CO_2-transporting pipelines or more modern-type high-strength pipeline steels [29,30]. In fact, all classes of approaches suffer from a combination of the following issues, especially when applied to high-strength and high-toughness steels or dense-phase CO_2 or CO_2-mixtures is being conveyed:

- **Estimation of dynamic fracture toughness**: Impact tests (e.g. the Charpy test) have traditionally been linked directly to the ability of the material to resist dynamic ductile crack growth (all Class 1 methods). For modern high-toughness steels, the correlation of impact energy to the fracture velocity and the arrest pressure becomes questionable, and the fracture resistance seems to be more dependent on the plastic flow properties of the steel [16]. Among most Class 3 approaches, impact tests [10,27] and similar tests [31] measuring the crack tip opening angle are also used [24] to evaluate the dynamic fracture resistance. In [25,26] a more physically-based elastic–plastic material description is used and cohesive zone elements are used to represent the dynamic fracture.
- **Fluid mechanics of two-phase decompression**: To obtain a physical description of RDF, it is essential to describe the spatially and temporally varying load on the pipe. Herein, a boiling two-phase fluid will sustain a higher pressure than a single-phase fluid. In the semi-empirical Class 1 approach, it is assumed that the fluid is in equilibrium, and it is implicitly assumed that the pressure profile, and hence the load profile on the pipe (even where the crack is open), does not substantially change from the conditions at which the experiments were carried out. In Class 3 approaches, simplifications are also made. In [25], a pressure profile is prescribed, while in [10], the fluid pressure is calculated based on computational fluid dynamics (CFD), but only the pressure at the crack-tip position is assumed to influence the fracture velocity.
- **Computationally demanding**: The Class 3 approaches, except the model in [27], require long computation times as they either rely on heavy 3D CFD computations [24], many-particle simulations [26], or rich structural finite-element meshes [25]. For the Class 3 approaches to serve as an alternative or complementary approach to the Class 1 approaches, computational efficiency is essential.

All existing approaches to RDF contain at least two of the issues listed above. One may therefore state that there is no existing efficient methodology for calculating the material parameters or pipe-wall thickness appropriate for arresting a propagating ductile fracture in a pipeline transporting dense-phase CO_2.

The objective of this work is to present a numerical methodology for FPC aiming to include the important physics and to be tractable for a desktop computer. In this way, a tool for safe and cost-effective design and operation of CO_2 pipelines can be established. The methodology comprises two main parts: a one-dimensional CFD model accounting for the fluid flow inside, and out of, the pipe, and a structure-mechanics model using the finite-element method (FEM) accounting for the non-linear mechanical behaviour of the pipe wall and employing a local stress-based fracture criterion. A two-way coupling between these two parts is implemented. This coupled fluid–structure model has been validated against crack-arrest experiments performed with methane and hydrogen [15,32], and it has later been extended to accurately account for two-phase (gas–liquid) and three-phase (gas–liquid–solid) CO_2 [13,33–35]. In the present work, the model is extended with an improved method to estimate the circumferentially varying pressure load on the fracture flaps, and a backfill model is employed to represent the material surrounding the pipe.

Recently, several research programmes have been initiated to prepare the industry for CCS and address the issue of FPC in CO_2 pipelines. The COOLTRANS project, run by National Grid (UK) has carried out and published results from five experiments connected to FPC in dense-phase CO_2 pipelines [11,36]. Two of these were full-scale crack-arrest experiments with a CO_2–N_2 mixture, and the conclusion was that the common method to address the FPC issue in pipelines, the Battelle Two Curve Method (BTCM) [20], 'is grossly non-conservative' [11] and 'not (currently) applicable to liquid or dense phase CO_2 or CO_2-rich mixtures' [12].

In the joint industry project CO2PIPETRANS, run by DNV-GL, a number of significant gaps in knowledge – in particular related to FPC – were identified in the recommended practice [37]. Two medium-scale crack-arrest experiments were performed in 2012 with dense-phase CO_2, and these results will be employed to validate the present fully coupled fluid–structure model. To our knowledge, this is the first time a coupled fluid–structure model has been validated with crack-arrest data for a CO_2 pipeline.

The rest of this paper is organized as follows: The crack-arrest experiments are described in Section 2, while Section 3 presents the coupled fluid–structure model. Section 4 describes how backfill is accounted for. All results are given in Section 5 and discussed in Section 6 before conclusions are drawn in Section 7. Appendix A presents the two-curve methods which we employ for reference.

2. The crack-arrest experiments

Two medium-scale crack-arrest experiments, identified as Test 1 and Test 2, with the original aim of evaluating the applicability of