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Energy Procedia 4 (2011) 3000–3007

Energy Procedia

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GHGT-10

CO_2 pipeline integrity: A new evaluation methodology

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Abstract

A coupled fluid-structure model for pipeline integrity simulations has been developed. The pipe material and fracture propagation have been modelled using the finite-element method with a local fracture criterion. The finite-volume method has been employed for the fluid flow inside the pipe. Choked-flow theory was used for calculating the flow through the pipe crack. A comparison to full-scale tests of running ductile fracture in steel pipelines pressurized with hydrogen and with methane has been done, and very promising results have been obtained. It is suggested that the current method may be useful in the design and operation of safe and cost-effective CO_2 transport systems.

Keywords: FEM; CFD; fluid-structure; fracture; pipeline; leak

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doi:10.1016/j.egypro.2011.02.210

1. Introduction

The transport of CO_2 is a necessary link between capture and storage sites in a carbon capture and storage (CCS) scheme. Some of the main challenges in CO_2 transport are related to pipeline integrity and fracture control and they comprise constructing suitable modelling tools, obtaining experimental data, and formulating new specifications and requirements when constructing the pipeline. Due to accidental failure (e.g. through third party impacts or corrosion) or planned maintenance, the pipe can be depressurized. The lower pressure will cause a phase change in the CO_2, resulting in a strong cooling of the pipe. If the temperature becomes low enough, the pipe material may become brittle, causing brittle rupture and severe damage to the pipeline.

Since CO_2 is toxic in higher concentrations, an integrity analysis of pipelines running through populated areas will be mandatory. Also, long running cracks in CO_2 pipelines may lead to significant economical losses, and must be avoided. At the same time, the high price of steel requires cost-effective solutions regarding the design of the pipeline.

Although avoidance of brittle fracture is the first step in fracture propagation control, we assume that this problem has been solved through e.g. using steel with a very low ductile brittle transition temperature. In this paper we focus on running ductile fracture (RDF), and on a new method to form pipeline design criteria (e.g. minimum thickness or fracture resistance demands) that make sure a RDF is arrested within an acceptable number of pipe lengths.

Running ductile fracture is commonly assessed using semi-empirically-based models originating from work done at the Battelle memorial institute in the 1970s [1]. These models assume the fluid and the structure (fracture resistance) to be uncoupled processes, and the RDF assessment is done through the “One Formula” or “Two-Curve Method”. Fracture resistance is empirically correlated to the Charpy energy, and the driving force is connected to the decompression velocity in the gas. As long as the fracture velocity (empirically derived from the Charpy energy needed for arrest in burst tests) is smaller than the decompression velocity, RDF-arrest is ensured. A variant of this model, known as the Japanese HLP approach [2], can in addition be used to predict the final crack length of a RDF.

Several drawbacks of the existing methods exist. For example, they require cumbersome re-calibration when new pressurised media inside the pipe, or when new material qualities are introduced. This approach was developed for pipeline material qualities used 30-40 years ago and worked well for the steel qualities used at that time. Due the economical benefits of transporting CO_2 at higher pressures and volumes, the trend seen today is to use pipelines with higher strength and toughness (e.g. the X100 and X120 qualities), as well as lower pipe thicknesses. The high toughness of these steels causes the relationship between the fracture energy (e.g. Charpy) and the fracture velocity to be rather dubious – leading to uncertain empirical correction factors for the crack velocity expressions [3].

A further challenge stems from the fact that the transported CO_2 will not be pure. The CO_2 mixture composition is dependent on the source; be it industrial processes, oil and gas processing or power generation, and also on the capture technology. Even small amounts of impurities can significantly influence the CO_2 thermodynamic and transport properties.

There are strong indications that the empirical basis developed earlier (Battelle and HLP) does not apply for these new conditions (e.g. [4]) In particular, there is a lack of knowledge on how CO_2 will influence on the running ductile fracture problem – both with regard to the depressurization wave speed as well as to the heat exchange aspects. One approach is to perform full scale pipe rupture tests, where the required pipe strength is derived from the toughness of the pipe section in which the propagating crack arrests. Such tests are very expensive and time consuming. Thus, they do not allow for thorough parametric studies. Concerns about the method have also recently been raised.

In this work, a procedure to simulate crack propagation and arrest through a coupling of fluid and structural/fracture mechanics has been investigated. The aim is to replace today’s empirical basis and to provide an alternative to expensive full scale testing, allowing for sensitivity studies in specific projects to be performed. The pipe has been modelled in the explicit finite-element (FE) code LS-DYNA [5] using shell elements. The fluid flow inside the pipe has been modelled using a one-dimensional (1D) finite-volume method. Choked-flow theory is used to model the gas flowing out of the pipe in the region where there is a crack opening.

The crack propagation is then driven by the internal pressure profile along a predefined crack path. The crack path is modelled as a predefined “seam” where the elements are allowed to fail. For validation of the methodology,

the results from the numerical simulations are compared with experimental data from full-scale testing of X65 steel pipelines containing high-pressure hydrogen and methane gas.

This work is one step towards the objective of developing a coupled (fluid-structure) fracture assessment model to enable safe and cost-effective design and operation of CO_2 pipelines by improving the fundamental understanding of the interaction between the material mechanical and fluid dynamical behaviour. A further objective is to establish requirements to avoid running ductile fracture in pipelines pressurized with CO_2 and CO_2 mixtures.

2. The pipeline model

The investigated pipeline material is an API 5L-X65mod ERW pipe, with an outer diameter of 267 mm and wall thickness of 6 mm. It is well known that pipe materials have a certain degree of anisotropic plastic behaviour [7, 8]. However, in this work we have used an isotropic yield function (von-Mises). The constitutive model assumes an associated flow rule and a nonlinear isotropic work-hardening rule. Fracture is modelled by the Cockcroft-Latham ductile fracture criterion [8].

The yield function, f , which defines the elastic domain in stress space, is expressed in the form

$$f\left(\boldsymbol{\sigma},\varepsilon_e\right)=\sigma_e\left(\boldsymbol{\sigma}\right)-\sigma_Y\left(\varepsilon_e\right)=0 \tag{1}$$

where $\boldsymbol{\sigma}$ is the stress tensor, σ_e is the von Mises equivalent stress, and ε_e is the corresponding equivalent plastic strain. The flow stress σ_Y is defined by the isotropic hardening rule

$$\sigma_Y=\sigma_0+\sum_{i=1}^{2}Q_i(1-\exp(-C_i\varepsilon_e)) \tag{2}$$

where σ_0 is the proportionality limit, and Q_i and C_i are hardening parameters. The hardening parameters in equation (8) were calibrated by using data from uniaxial tensile tests from specimens oriented in the circumferential direction of the pipe, giving: σ_0 = 521.8 MPa, Q_1 = 183.5 MPa, Q_2 = 3655 MPa, C_1 = 39.1, C_2 = 77.3. When calibrating the uni-axial hardening curve, the triaxial stress state encountered in the neck of the circular specimen was taken into account.

An uncoupled approach to describe fracture is adopted. This means that the influence of damage evolution on the material behaviour is neglected, thus there is no material softening before initiation of fracture. Crack propagation is described by element erosion when a fracture criterion is fulfilled within the element:

$$W=\int\max\left(\sigma_1,0\right)d\varepsilon_e\le W_c \tag{3}$$

where σ_1 is the maximum principal stress, and W_c is the value of the Cockcroft-Latham integral W giving fracture. This criterion implies that fracture is a function of the tensile (principal) stress σ_1 and equivalent plastic strain ε_e, and has the dimensions of work per unit volume. In the present study, the fracture parameter was identified from uniaxial tension tests: W_c = 1200 MPa.

The FE-mesh of the short steel pipeline (Methane gas simulations) consists of 28980 Belytschko-Tsay shell elements with 5 through-thickness integration points - giving a characteristic element length of 12.5 mm. The crack is then driven by the internal pressure profile along a predefined crack path. As illustrated in Figure 1, this crack path is modelled as a predefined "seam" where the elements are allowed to fail.

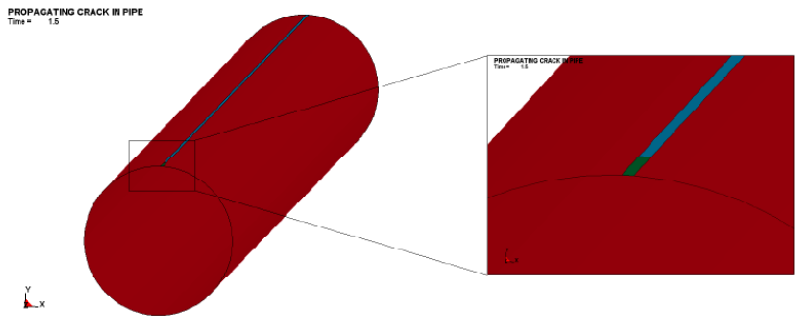


Figure 1. The 3 parts of the pipe in LS-DYNA: main pipe wall (red), "explosive charge" (green), crack path (blue).

3. The fluid model

This section briefly describes the fluid model and its numerical solution.

3.1. Governing equations

The 1D flow of a single-phase fluid through a pipeline can be modelled at time t and position x by the 1D Euler equations,

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} &= -\varsigma_e, \\ \frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial p}{\partial x} &= -u\varsigma_e, \\ \frac{\partial E}{\partial t} + \frac{\partial \left[(E+p)u\right]}{\partial x} &= -(E_e + p_e)\frac{1}{\rho_e}\varsigma_e, \end{aligned} \tag{4}$$

where ρ and u are the density and the x-directed velocity, respectively. The total specific energy of the fluid can be written $E = e + u^2/2$, where e is the internal specific energy.

The right-hand side of these equations has been added to the original Euler equations, to represent the leakage of the fluid through a crack in the pipeline. The additional source term factor ς_e represents the mass loss due to the leakage.

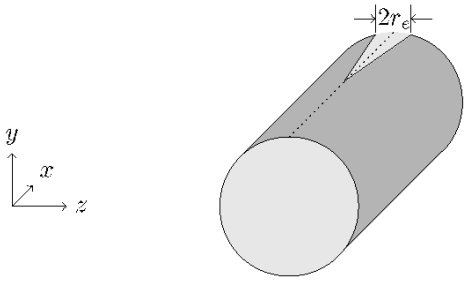


Figure 2. The crack propagates along the x-direction, leaving behind a growing opening of width $2r_e(x)$ in the pipe. As the crack symmetrically propagates in both directions, only half of the domain is shown.

Ahead of the crack tip, it is reasonable to assume the flow to be 1D but this assumption does not hold behind the crack tip. However, the added source term can effectively account for the y-directed escape flow due to the initial leakage of the fluid through the crack opening. As the opening widens, the 1D character of the fluid flow will naturally degenerate, but this is believed to be less important with respect to the crack propagation.

With a suitable equation of state (EOS), the escape quantities, denoted with subscript e, can be expressed as functions of the state of the fluid within the pipe, as well as of the crack opening width $2r_e(x)$ and the surrounding pressure. For single-phase flow of gases well above their critical point, the ideal gas EOS

$$p = (\gamma - 1)e\rho\,, \tag{5}$$

where $\gamma = c_p/c_v$ is the ratio of the specific heats, works sufficiently well. Initially, when the inside to outside pressure ratio is larger than or equal to $[(\gamma + 1)/2]^{\gamma/(\gamma - 1)}$, the flow velocity will attain the speed of sound, i.e. the flow is choked. If one assumes that the escape flow is an isentropic process, the following expressions results:

$$\rho_e = \rho \left(\frac{2}{\gamma + 1} \right)^{1/(\gamma - 1)}, \tag{6}$$

$$u_e = a_e = a\sqrt{\frac{2}{\gamma + 1}}, \tag{7}$$

where a is the speed of sound. When the inside to outside pressure ratio falls below the choked flow criterion, it is still possible to derive the corresponding expressions,

$$\rho_e = \left(\frac{p_a}{p} \right)^{1/\gamma} \rho, \tag{8}$$

$$u_e = a\left\{ \frac{2}{\gamma - 1}\left[1 - \left(\frac{p_a}{p} \right)^{(\gamma - 1)/\gamma} \right] \right\}^{1/2}. \tag{9}$$

For an on-shore pipeline, the surrounding pressure p_a usually corresponds to the atmospheric pressure, and that has been assumed in the following calculations.

3.2. Numerical solution

The governing equations (4) are discretized using the Finite-Volume method. They are then solved numerically employing the multi-stage centred (MUSTA) scheme by Toro and coworkers [9, 10]. Details are omitted here for brevity. The MUSTA scheme has been investigated and found to be robust and accurate for different two-phase flow models, including drift-flux [11, 12] and two-fluid [13] models. It is therefore considered that the MUSTA scheme may work well for later extensions of the present model to account for phase transfer, etc.

4. The fluid-structure coupling scheme

A numerical methodology for simulation of crack propagation and arrest through a coupling of fluid and structural/fracture mechanics has been established in this work. The pipe has been modelled in the explicit finite-element (FE) code LS-DYNA using shell elements. The fluid flow inside the pipe has been modelled using a one-dimensional (1D) finite-volume method where in any cross-section, the pressure is taken to be uniform. The coupling between LS-DYNA and the fluid code is done through a user-defined loading subroutine in LS-DYNA where the fluid code is called. At each time step, the fluid code calculates an updated pressure profile for the longitudinal direction of the pipe. This pressure is applied as a load in the structural FE code. Dynamic fracture is

initiated by removing a number of elements corresponding to the length of the directed explosive charge in the experiment (total of 0.3 m)

5. Numerical simulations

The proposed numerical methodology for evaluation of running ductile fracture in steel pipelines has been validated by comparing numerical predictions of fluid pressure crack propagation length with experimental measurements obtained from full-scale testing: A series of four full scale burst tests have been conducted on API 5L-X65mod. ERW pipes with outer diameter of 267 mm and wall thickness of 6 mm. Two tests were performed with hydrogen gas with initial pressure equal to 121 and 151 bar. Furthermore, two tests were performed with methane gas with initial pressure equal to 122 and 152 bar. The hydrogen gas tests were performed on longer pipes to avoid that the reflecting gas-decompression wave could reach the crack tip before arrest. Illustrations of the test set-ups are shown in Figure 3. For more details about the full scale testing, it is referred to the publication by Aihara et al. [14].

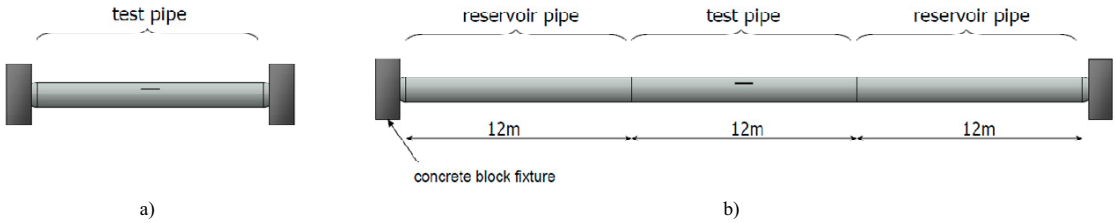


Figure 3. Schematic illustration of a) Methane gas test setup and (total 11.5 meter) b) Hydrogen gas test setup (total 34.5 meter).

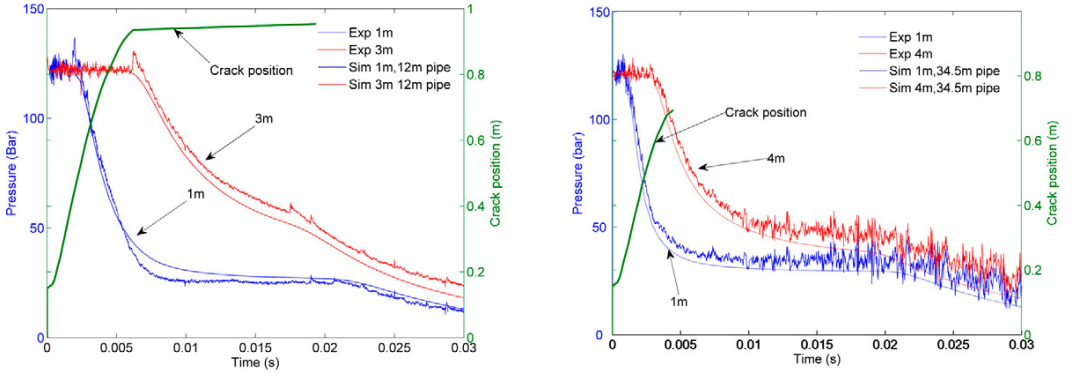
Pressure transducers were placed at a distance of 1 m and 3 m from the initial crack for the methane gas tests, and 1 m and 4 m for the hydrogen gas tests.

In the numerical simulations, a spatial resolution of 14 mm along the pipe axis was used for both the pipeline model and the fluid model. Furthermore, the Courant–Friedrichs–Lewy number for the fluid part of the simulations was set to 0.9. The parameter values for the EOS (5) are summarized in Table 1.

Table 1. EOS parameter values used in the simulations.

	$\gamma = c_p/c_v$	c_p (J kg^{-1} K^{-1})
Hydrogen, 121 bar	1.5307	12784
Hydrogen, 151 bar	1.5596	12557
Methane, 122 bar	1.6153	1114.1
Methane, 152 bar	1.8059	933.72

Table 2 shows a comparison between the predicted and experimental fracture-propagation length. It is seen that the numerical predictions show a very good agreement with the experimental measurements. Furthermore, as demonstrated by Figure 4 for the case of methane gas test with initial internal pressure equal to 122 bar and hydrogen test with initial internal pressure equal to 121 bar, the predicted and measured pressure in the pipeline are very similar.



a) b)

Figure 4. Comparison of predicted and measured pressure in pipeline, a) methane gas pressurized at 122 bar and b) hydrogen gas pressurized at 121 bar.

Table 2. Comparison of predicted and experimental fracture propagation length.

	Simulated length (m)	Experimental length (m)
Hydrogen, 121 bar	0.55	0.60-0.70
Hydrogen, 151 bar	0.60	0.75-0.80
Methane, 122 bar	0.80	0.91
Methane, 152 bar	0.90	1.16

6. Conclusion

A coupled fluid-structure model for pipeline integrity simulations has been developed. A comparison of numerical predictions and experimental data obtained from full-scale testing of running fracture in steel pipelines pressurized with hydrogen and methane gives very promising results. This work is one step towards the objective of developing a coupled (fluid-structure) fracture-assessment model to enable safe and cost-effective design and operation of CO_2 pipelines by improving the fundamental understanding of the interaction between the material-mechanical and fluid-dynamical behaviour. A further objective is to establish requirements to avoid running ductile fracture in pipelines pressurized with CO_2 and CO_2 mixtures.

Acknowledgments

This publication has been produced with support from the BIGCCS Centre, performed under the Norwegian research programme *Centres for Environment-friendly Energy Research (FME)*. The authors acknowledge the following partners for their contributions: Aker Solutions, ConocoPhilips, Det Norske Veritas AS, Gassco AS, Hydro Aluminium AS, Shell Technology AS, Statkraft Development AS, Statoil Petroleum AS, TOTAL E&P Norge AS, and the Research Council of Norway (193816/S60).

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