PIPELINE FLOW MODELLING WITH SOURCE TERMS DUE TO LEAKAGE: THE STRAW METHOD

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Pipelines are a common and convenient way of transporting natural gas, and with the increasing interest in carbon capture and storage (CCS) technology, pipeline transport will also become an important link between the capture and storage sites of CO_2. In order to control and predict the risk of accidental failure, such as illustrated in Figure 1, the fracture properties of the pipe materials have long been a subject of study. A semi-empirical model based on research at the Battelle memorial institute in the 1970s [1] where the fluid flow and the material structure behaviour are assumed to be uncoupled processes, is traditionally used for the assessment of running ductile fractures. New pipeline materials have, however, motivated the search for improved models, and it is natural to consider a coupling of the fluid and structure processes. Moreover, the thermodynamic properties of CO_2 are different from those of natural gas at the relevant conditions for pipeline transport. It is not clear how e.g. phase change and a large heat capacity will influence the fracture mechanics. Further, various impurities will be present in the transported CO_2, and even small amounts will change the properties compared to pure CO_2. Therefore, a flexible framework is required with respect to the employed equations of state.

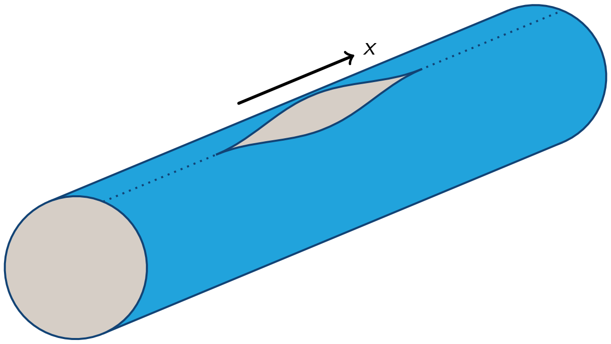

Figure 1. A section of the pipeline with a fracture running along the *x*-direction.

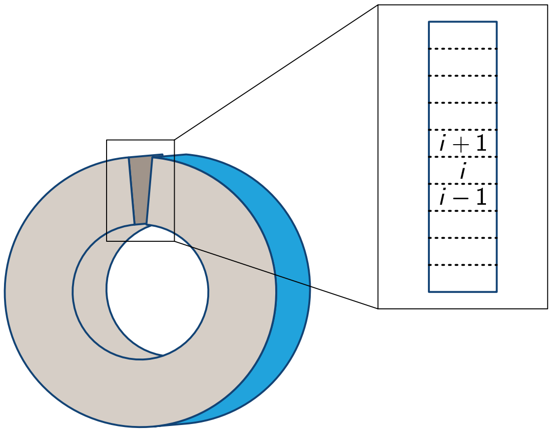

Figure 2. A small section of the pipe where the exaggerated pipe wall is partly open due to a crack. The flow rate through the opening is evaluated separately by modelling the crack as a sequence of small tubes, or straws, transversal to the main pipe as indicated. Each tube is discretized into finite volumes *i*.

In Berstad et al. [2], a coupled fluid-structure model was presented and tested by comparisons to full-scale experiments of running ductile fractures in steel pipelines. In this model, the effect of the leakage of the fluid through the crack opening is included in the one dimensional fluid equations as source terms. In order to evaluate these, the leakage is assumed to be an isentropic process, and by using the ideal gas equation of state it is possible to derive analytical expressions for the source terms. The model agreed well with the experiments, but is restricted to the ideal gas case. A generalization of the model to handle other equations of state may follow two paths, either an analytical approach where the source terms are derived explicitly as in [2], or a numerical approach in which the source terms are calculated using the flow solver. It is the latter that will be studied here, and it will be referred to as "the straw method".

The straw method takes the fracture geometry as given. The main challenge is to evaluate the flow rate through the fracture. For a two-phase flow with a "black box" equation of state, an attempt to develop analytical expressions for choked flow may lead to intractable expressions. An alternative idea is then to let the flow rate be evaluated by a numerical solver analogously to what happens inside the pipe. We assume here that the fracture along the pipe can be modelled by a sequence of transversal tubes, whose length is the thickness of the pipe steel. These tubes are plugged into the main pipe, and their cross-sections represent the crack opening (see Figure 2). The fluid dynamics in the tubes, as well as in the pipe, is solved as one-dimensional conservation laws averaged on the cross-section. By inserting one tube in each of the fractured pipe cells, we obtain a discretization of the fracture along the pipe. The variation of the fracture width is represented by adjusting the tube diameters at each time step. The propagation of the fracture is accounted for by adding new tubes along the pipe.

The inlet flows in the transversal sub-tubes become mass, momentum and internal-energy source terms for the flow in the main pipe. To simplify, we assume that the flow in the pipe is quasi-stationary with regard to the flow through the fracture, therefore we let the sub-tubes reach steady-state flow between the pipe and outside pressures at all time steps. This allows solving them independently of the pipe. Particular attention has to be given to the boundary conditions for the sub-tubes, depending on whether the outflow is choked or not.

Our initial results show that the straw method works well, but that it is computationally expensive, so that it should be applied mainly where analytical expressions are not available.

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