Towards an improved prediction of fracture behavior in pipelines using the coupled fluid-structure interaction (FSI) model

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ABSTRACT

The paper focuses on the improved description of the decompression behavior of the gas mixtures transported in the long-distance steel pipelines and its influence on the ductile fracture propagation and arrest. In contrast to current methodologies, the presented approach includes fully coupled fluid-structure interaction (FSI) modeling based on the Coupled Eulerian-Lagrange (CEL) method. The simulation of the ductile fracture behavior of the pipeline steels is carried out using the modified Bai-Wierzbicki (MBW) model. The fluid behavior is described by Euler equations and the equation of state (EOS) GREG-2008. The Mohr-Coulomb (MC) model is applied to account for the influence of the soil backfill on the pipe deformation. The developed coupled FSI modeling approach is verified against the results from the full-scale burst test (FSBT) with CO₂-rich mixture. The proposed methodology allows for an efficient and reliable prediction of the fracture behavior of pipelines transporting various gas mixtures.

KEY WORDS: Fluid-structure interaction model; running ductile fracture; MBW model; steel pipeline; CO₂-rich mixture.

INTRODUCTION

Ensuring resistance to running-ductile fracture is one of the most important safety requirements for gas transmission pipelines. However, the ductile fracture control is still an open issue especially when dealing with the new generations of steels and transport of multi-component, rich gas mixtures. The current testing and prediction methods for ductile fracture controls exhibit limitations originating from an inadequate definition of material requirements, insufficient description of the gas decompression behavior and its interaction with pipe structural performance.

One viable solution towards an improved crack arrest prediction lies in the development and application of a 3D coupled Fluid-Structure-Interaction (FSI) modelling approach. In addition to a more accurate estimations of the propagation and arrest properties, the FSI methodology also allows a better understanding of the mechanisms that control them. One of the biggest challenges in the development of the FSI methodology is the trade-off between model complexity and computational efficiency. The complexity results from the coupled description of the 3D structural, fracture, fluid decompression and soil backfill behavior. To achieve adequate CPU time, complexity must be reduced as much as necessary without losing the required accuracy. In addition, a detailed test program needs to be established and carried out, covering the steps of characterization, calibration and validation. Especially the latter poses the significant challenge, as it involves the comparison with the cost- and time-intensive full-scale burst tests (FSBTs). This step is crucial for the assessment of the accuracy and feasibility of the FSI approach. However, usually, due to the lack of the FSBTs, the FSI approach can only be verified but not validated by comparing its prediction with the results of already available FSBTs on similar pipeline materials. Talemi et al. (2019) and Keim et al. (2019a) applied modified Bai-Wierzbicki (MBW) model for simulation of ductile fracture in API grade X70 steel. The model was able to correctly reproduce the global load-displacement response of DWTT specimen extracted from plate material. Talemi et al. (2019) combined the MBW and the 1D CFD models to simulate the FSBT from Inoue et al. (2003) on the buried X70 pipelines. The influence of the soil backfill on the pipe deformation was considered by a simplified approach with a constant pressure applied on the outer surface of the pipe as suggested in Makino et al. (2001). Aursand et al. (2016), Nordhagen et al. (2017) and Gruben et al. (2018) were able to validate their FSI model against the results from FSBTs on CO₂ pipelines. The pipe structural and fracture behavior were represented by J2 plasticity model and Cockcroft-Latham ductile fracture criterion. While the two-directional fluid flow has been calculated using 1D homogeneous equilibrium model (HEM), the thermodynamic properties resulted from Span–Wagner and Peng–Robinson equations of state (EOS). Smooth-particle method (SPH) with the Mohr-Coulomb (MC) model was used to describe the mechanical behavior of the soil. To reduce computational time, the FE model of the pipe was discretized by shell elements. Gruben et al. (2018) demonstrated a distinct influence of the backfill material on the propagation and arrest and thus the importance of an accurate description of its properties. Furthermore, they indicated that more than half of the total energy from the escaping fluid was dissipated in the surrounding clay and less than 3% in fracture. Keim et al. (2019b) used the coupled Euler-Lagrange (CEL) method to link MBW and fluid models. Compared to the other approaches, the fluid model based on the GREG-2008 EOS by Kunz and Wagner (2012) directly provides 3D pressure distributions in the pipe during fracture propagation. The verification of the fluid model was conducted based on...