Quantitative Safety Assessment of Hydrocarbon Transportation Pipelines

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Modelling of heat transfer and flow in a soil surrounding a pipeline with a leak

Technical Note

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1. Introduction

An accidental leak in a pressurized pipeline, for example as a result of corrosion, will be accompanied by the rapid quasi-adiabatic expansion of the escaping fluid. In the case of some hydrocarbon pipelines, especially ethylene, the escaping fluid may reach temperatures as low as –104 °C [1]. In such circumstances, a significant concern is the risk of the pipe wall temperature in contact with the escaping fluid eventually reaching the pipe material Ductile to Brittle Transition Temperature (DBTT), possibly leading to a propagating brittle fracture.

In order to predict the pipe wall temperatures when assessing the pipeline brittle fracture, the pipeline decompression model developed in Task 1a needs to be coupled with a model resolving the heat transfer in the surrounding soil. The latter requires evaluating the heat transfer and dispersion flow from a leaking buried pipeline.

This report summarizes results of preliminary modelling of expansion flow of ethylene from a small leak in a buried pipeline. The study has been performed with the view of experiments planned in Task 2 of the project.

2. Mathematical model

To describe a steady-state flow and heat transfer in a gas moving through a soil, a fixed-bed porous flow model is applied in the present study. The flow is modelled using the following set of coupled equations, describing the mass, momentum and energy conservation, augmented by Forchheimer equation [2], are applied:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = \nabla \cdot \left[-p\mathbf{I} + \mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^{T}\right) - \frac{2}{3}\mu(\nabla \cdot \mathbf{u})\mathbf{I} \right] + \mathbf{F} \tag{2}$$

$$\frac{1}{\epsilon_p}\rho(\mathbf{u} \cdot \nabla)\mathbf{u}\frac{1}{\epsilon_p} = \nabla \cdot \left[-p\mathbf{I} + \mu\frac{1}{\epsilon_p}\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^{T}\right) - \frac{2}{3}\mu\frac{1}{\epsilon_p}(\nabla \cdot \mathbf{u})\mathbf{I} \right] - \left(\mu\kappa^{-1} + \beta_F|\mathbf{u}| + \frac{Q_{br}}{\epsilon_p^2} \right)\mathbf{u} + \mathbf{F} \tag{3}$$

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_p + Q_{vd} \tag{4}$$

The Forchheimer coefficient, β_F, is defined as:

$$\beta_F = \frac{\rho \epsilon_p C_f}{\sqrt{\kappa}} \tag{5}$$

where C_f is the friction coefficient:

$$C_f = \frac{1.75}{\sqrt{150\epsilon_p^3}} \tag{6}$$

3. Geometry, mesh and flow parameters

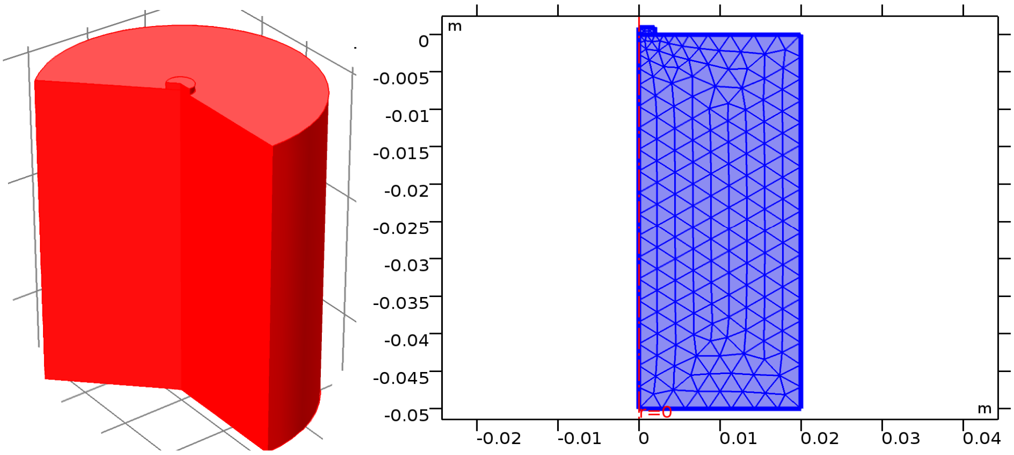

Figure 1. 2D axy-symmetrical geometry and computational mesh.

In the present study the flow is modelled for a part of the domain covered by a circular cylinder (Figure 1). The domain occupied by the granular material was set to be 0.5 m deep and 0.4 m in diameter. At the top the domain is extended to include a short section representing the release orifice of 4 mm diameter.

The porosity of the sand was set to ϵ_p=0.4, while the permeability, κ, was varied between 10^{-9} and 10^{-7} m^2. These values are typical for porous beds formed of spherical particles of diameters ranging from 1 to 6 mm [3].

At the release orifice the gas velocity and pressure were set respectively to 10 m/s and 10 bar.

4. Results

Figures 2 and 3 show respectively the velocity and temperature variation in the soil domain (Figure 1) predicted as a result of solution of the set of the flow equations (1)-(4) for the case described in section 2 using COMSOL Mutliphysics 5.3 package [4].

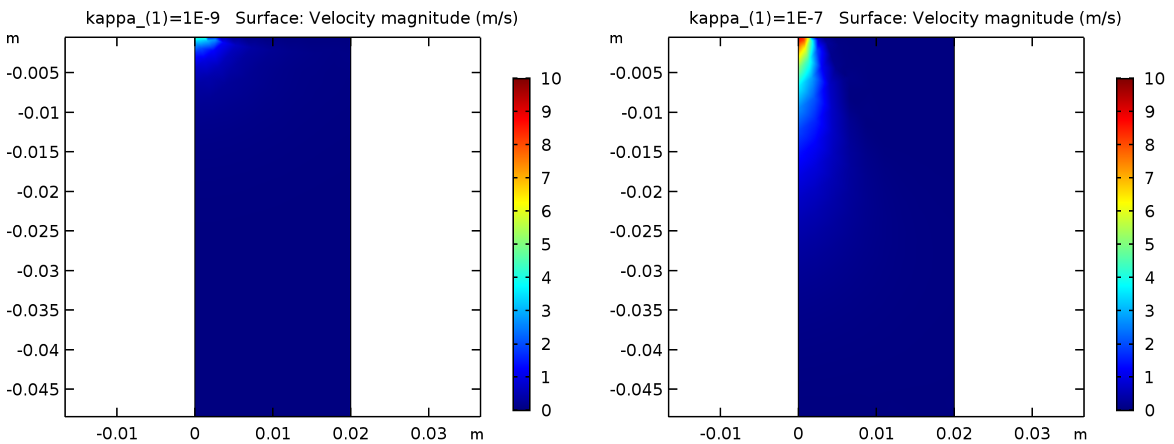

Figure 2. Velocity field.

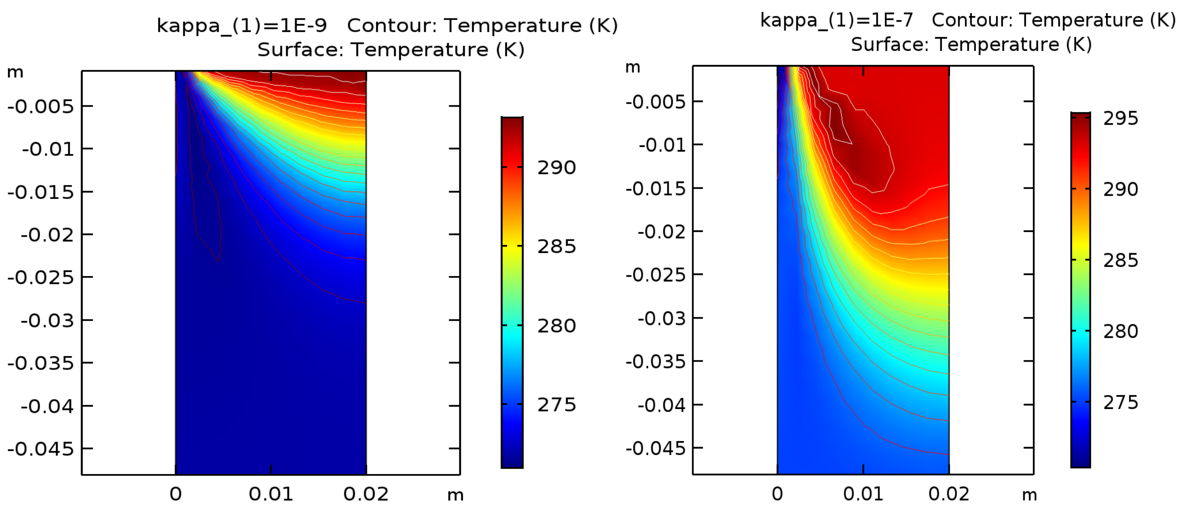

Figure 3. Temperature field.

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