Quantitative Safety Assessment of Hydrocarbon Transportation Pipelines

Qatar National Research Fund

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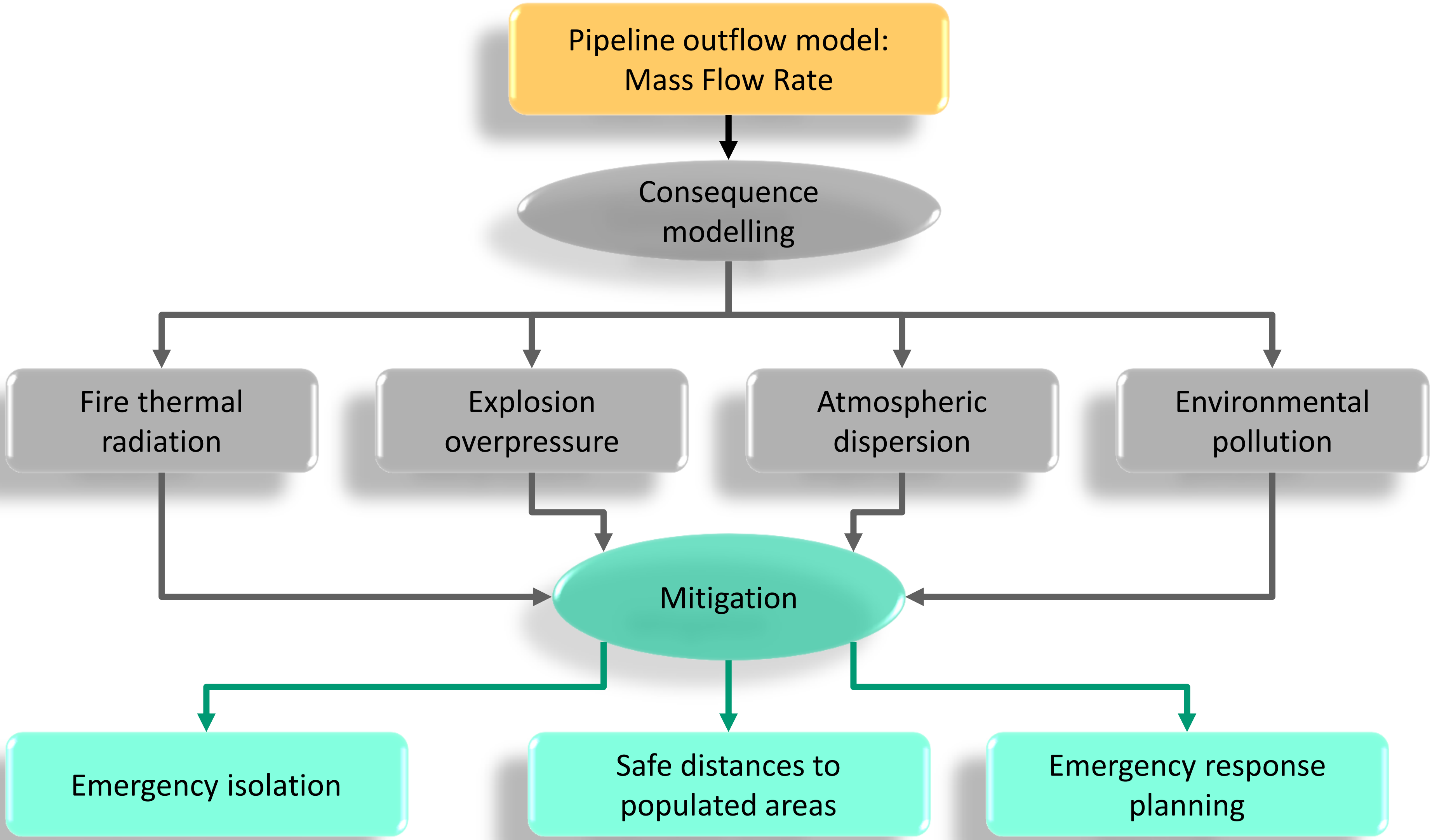
Presentation outline

- Background
- Objectives and scope
- Recent progress
  - Pipeline decompression modelling
  - Physical properties models
  - Experimentation
- Further work

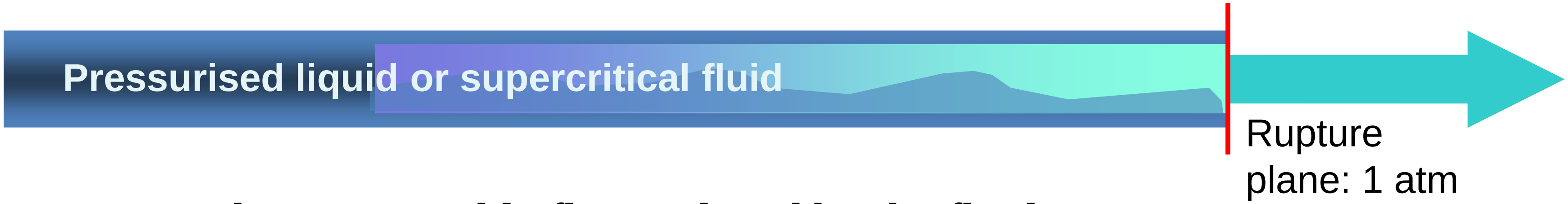
Ethylene pipelines

- High-pressure pipelines enable cost-effective transportation of large amounts of fluid over long distance
- In Qatar, a recently constructed **135 km long pipeline transports ethylene** from Ras Laffan Industrial City to Q-Chem II and QATOFIN plants in Mesaieed Industrial City to produce high and low density polyethylene
- Ethylene is a highly flammable material and therefore safe design/operation of ethylene pipelines is of paramount importance

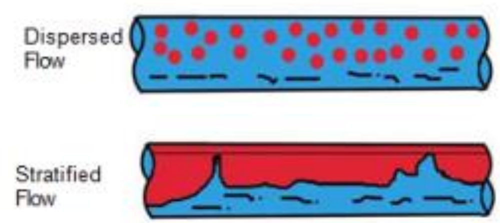
Quantitative Risk Assessment



Pipeline decompression phenomena



- Unsteady compressible flow induced by the fluid expansion to atmosphere at the rupture plane
- Phase transition in the expansion wave in the pipe
- Cooling induced by expansion in the flow
- Strong variation of physical properties of the phases with pressure and temperature
- High density ratio of the liquid and vapour phases can lead to stratification of the phases



- The accurate modelling of outflow following pipeline rupture is highly challenging

Outflow Modelling Challenge

- In the past the models have been validated against very limited number of measurements

and there is no real validation data for ethylene

- Coupling an outflow model with an accurate EoS is another important aspect of development of modelling

- Currently there **are no reliable validated models, accounting for complexity of the flow and real-fluid behaviour**, suitable for QRA of ethylene pipelines

The Project Objectives & Scope

Objective 1 (Lead: UCL):
Mathematical modelling

Develop state-of-the-art simulation tools for the quantitative risk assessment of hydrocarbon pipelines, based on accurate predictions of **transient outflow** and **thermodynamic properties** of fluid during pipeline depressurization

Objective 2 (Lead: TAMU-Qatar):
Experimental validation

Perform **ethylene pipeline rupture tests** to obtain experimental data for validation of outflow model developed

Objective 3 (Lead: TAMU-Qatar):
Case study

Demonstrate the usefulness of the tools developed by applying them to a realistic pipeline in Qatar.

Objective 4 (Lead: TAMU-Qatar):
Communication

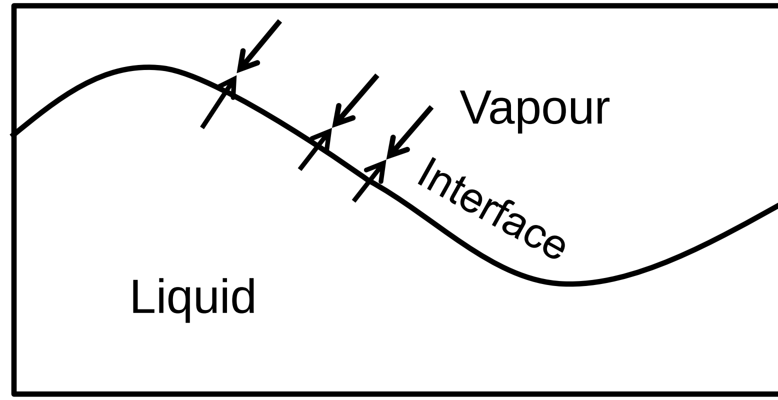
Pipeline Outflow Model

Development of a heterogeneous two-phase flow model, accounting for:

- Transient compressible nature of the flow;
- Flow regime dependent wall friction and heat transfer;
- Heat capacity of the pipe wall;
- Puncture size and location on the pipe;
- Physical properties of a multicomponent fluid, predicted using validated Equation of State (EoS) models

Pipeline Outflow Model

Conservation equations:



$$\frac{\partial \alpha_i \rho_i}{\partial t} + \frac{\partial \alpha_i \rho_i u_i}{\partial x} = S_\rho$$

$$\frac{\partial \alpha_i \rho_i u_i}{\partial t} + \frac{\partial \alpha_i \rho_i u_i^2 + \alpha_i P_i}{\partial x} = P_i \frac{\partial \alpha_i}{\partial x} + S_u$$

$$\frac{\partial \alpha_i \rho_i E_i}{\partial t} + \frac{\partial \alpha_i \rho_i H_i}{\partial x} = -P_i u_{int} \frac{\partial \alpha_i}{\partial x} + S_e$$

$$\frac{\partial \alpha_v}{\partial t} + u_{int} \frac{\partial \alpha_v}{\partial x} = S_i$$

Source terms are flow regime dependent

where α is the volume fraction as function of time t and space x;

ρ, E, H and P are density, total energy, total enthalpy and pressure of the individual phases

Physical properties models

Phase equilibrium
Physical Properties:
- Density
- Heat Capacity
- Sonic Velocity
- Joule-Thomson Coefficient
- Isothermal Compressibility

Transport Properties:
- Viscosity
- Diffusivity
- Thermal conductivity

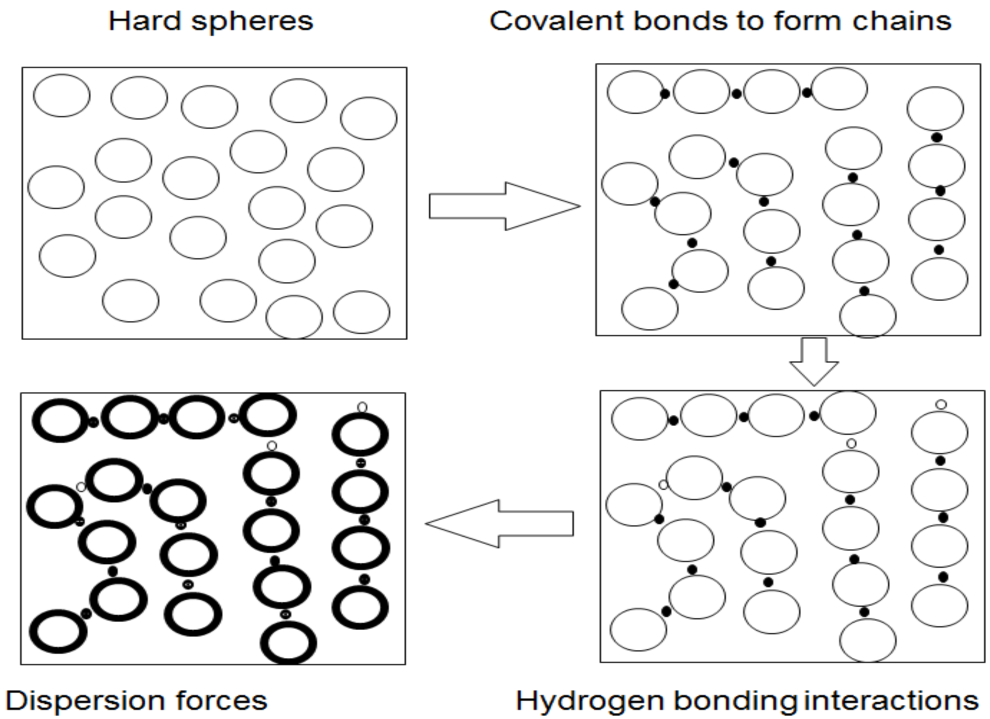
Rigorous mathematical model for pipeline rupture:
- Mass conservation
- Momentum conservation
- Energy conservation
- Multiphase heterogeneous flow
- Interphase mass and heat transfer
- Fluid/structure interaction

Thermodynamic models

- Peng – Robinson (PR) EoS:

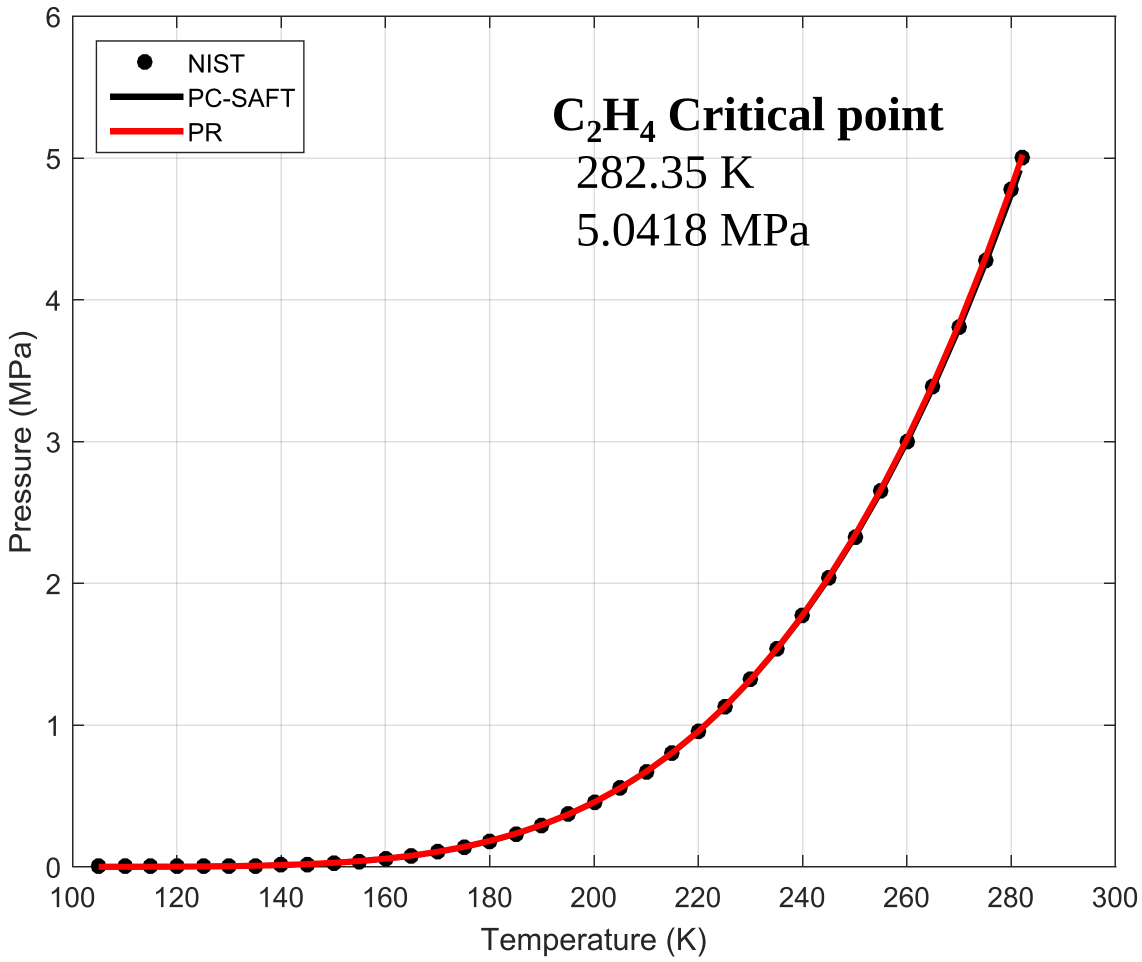
$$P = \frac{RT}{v - b} - \frac{a(T)}{v(v + b) + b(v - b)}$$

- Perturbed Chain – Statistical Association Fluid Theory (PC-SAFT) EoS:

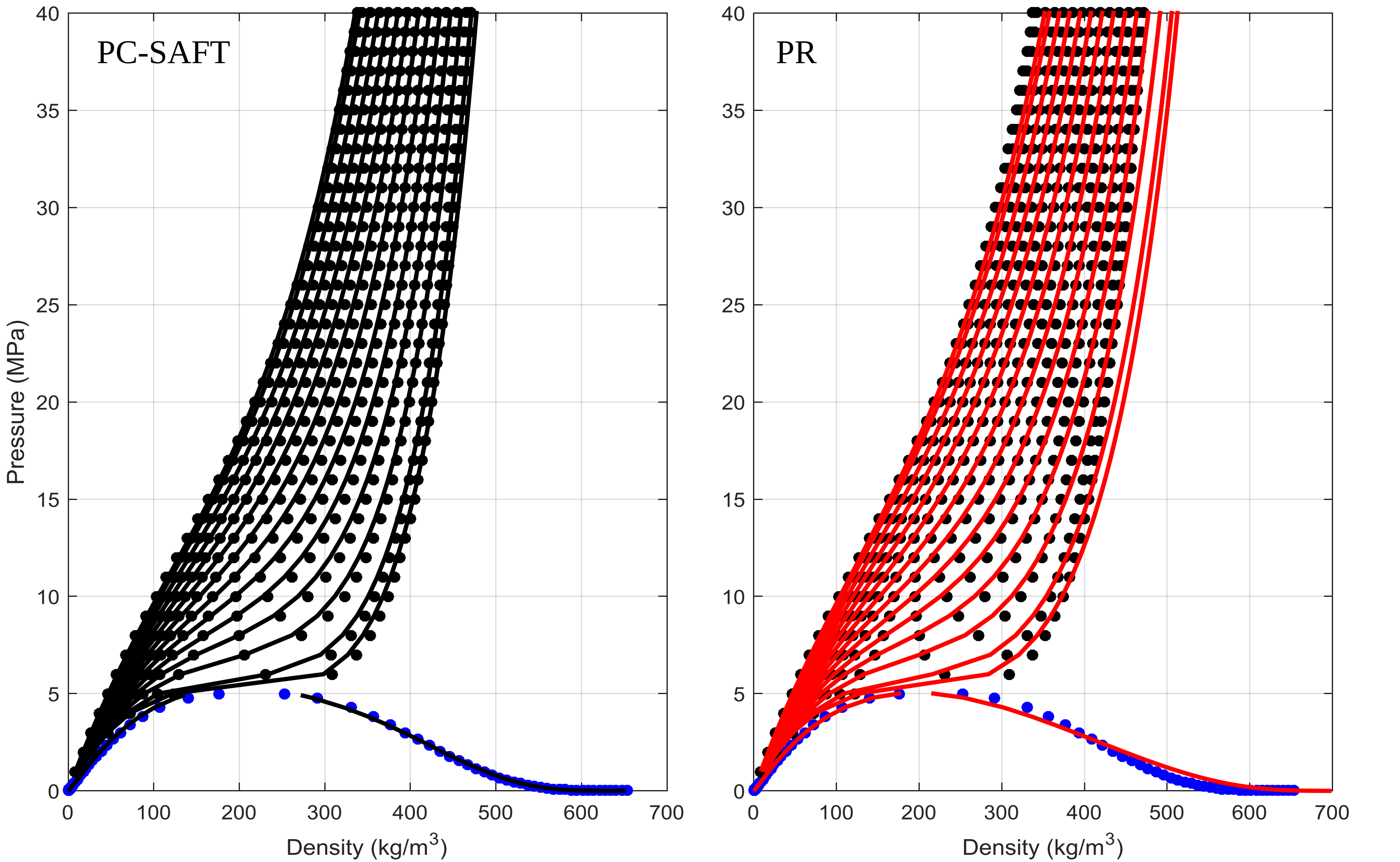


$$\frac{A^{res}(T,\rho)}{NRT} = \frac{a^{hs}(T,\rho)}{RT} + \frac{a^{chain}(T,\rho)}{RT} + \frac{a^{disp}(T,\rho)}{RT} + \frac{a^{assoc}(T,\rho)}{RT}$$

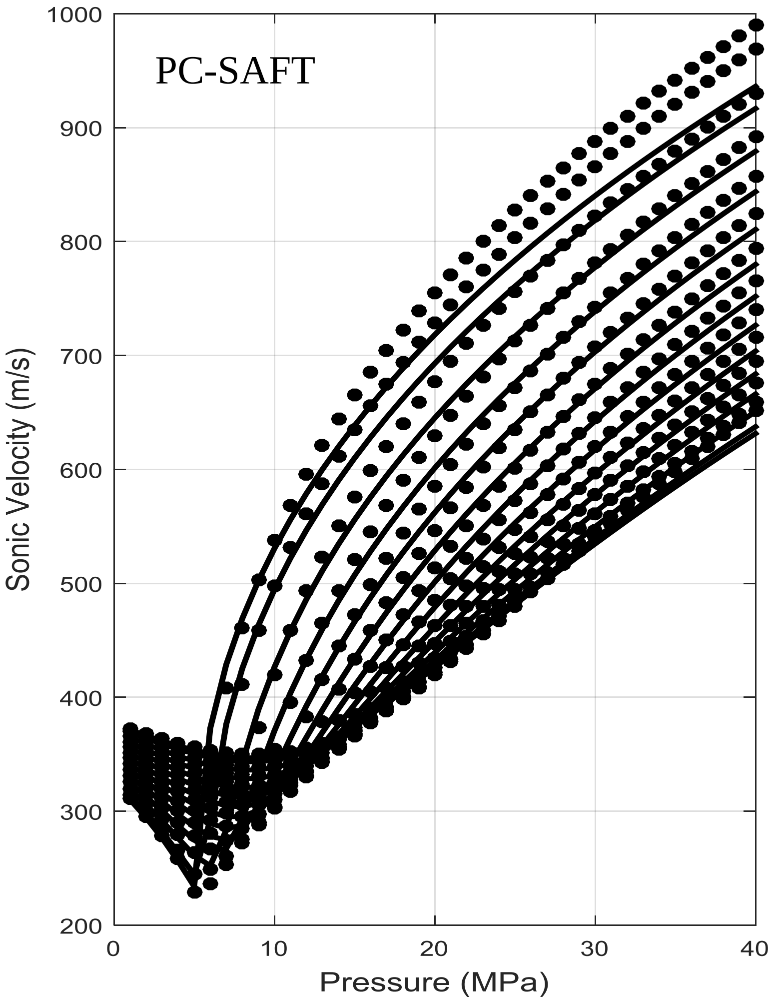
Ethylene Vapor Pressure

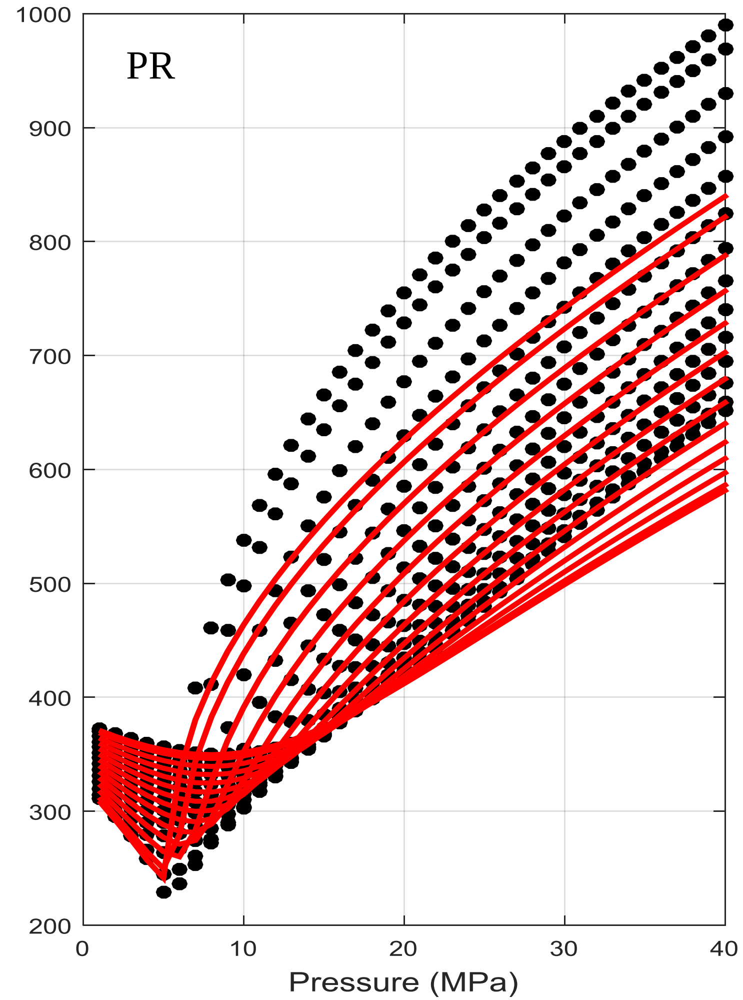


Ethylene Density

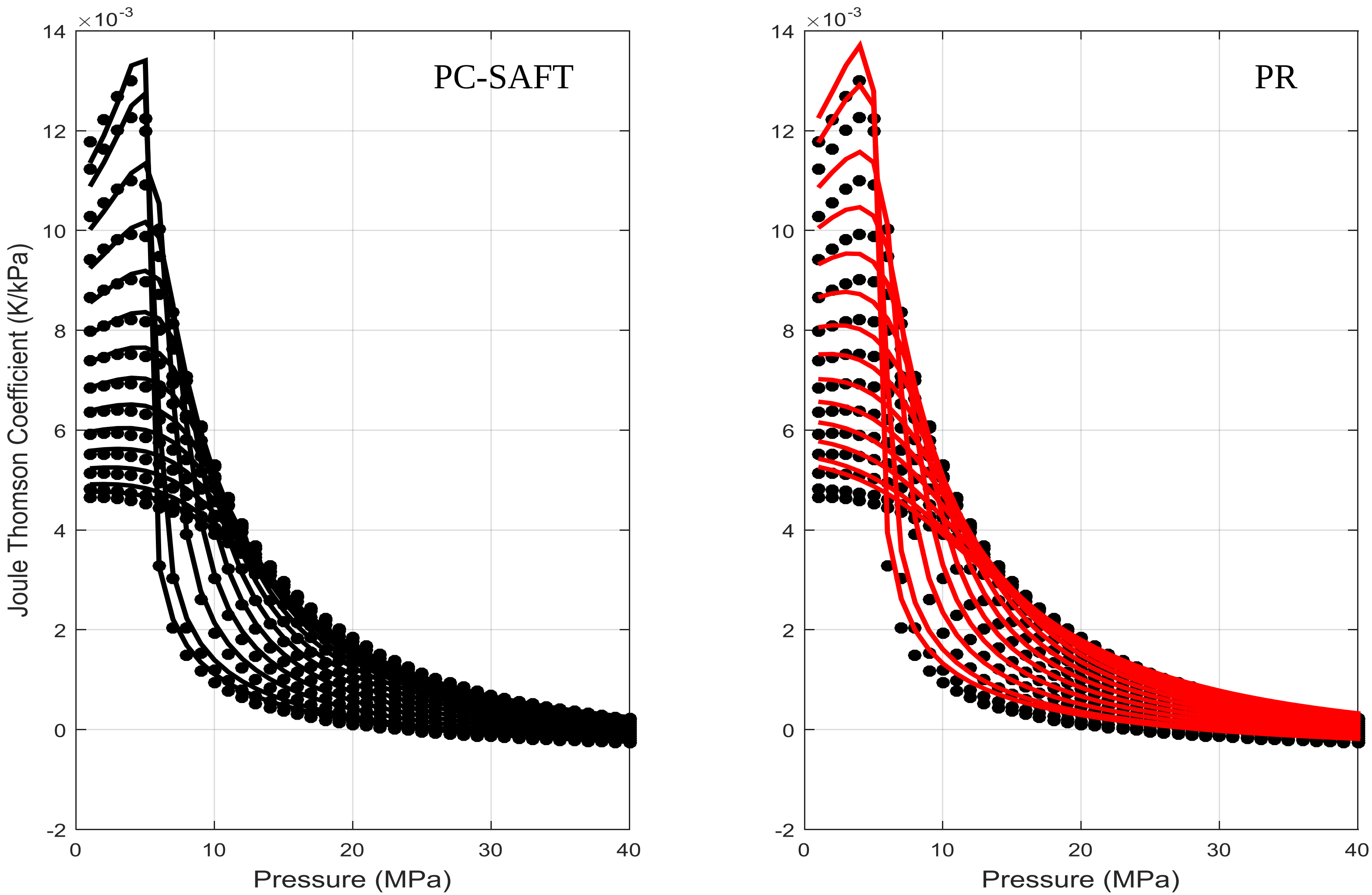


Ethylene Speed of Sound

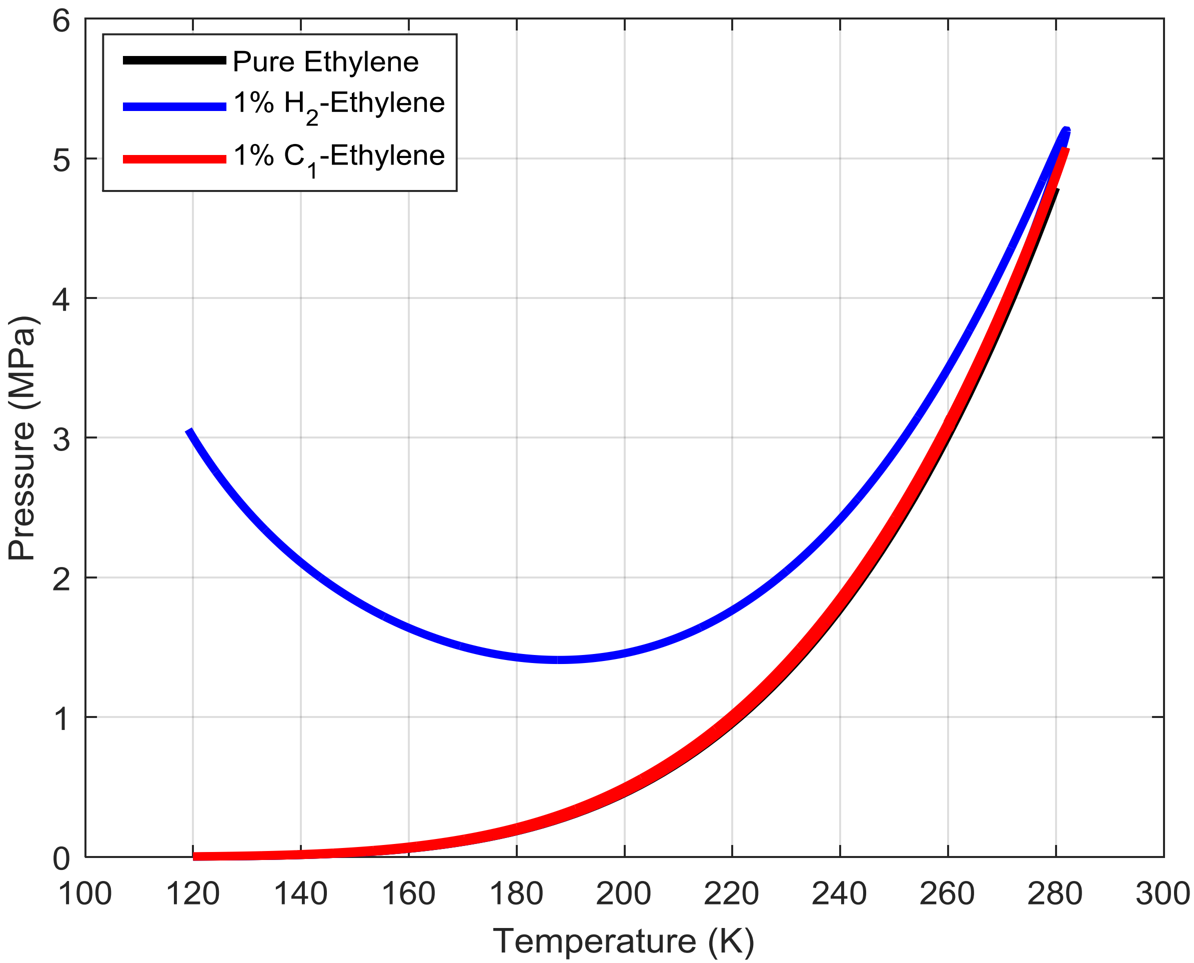




Ethylene Joule-Thomson Coefficient



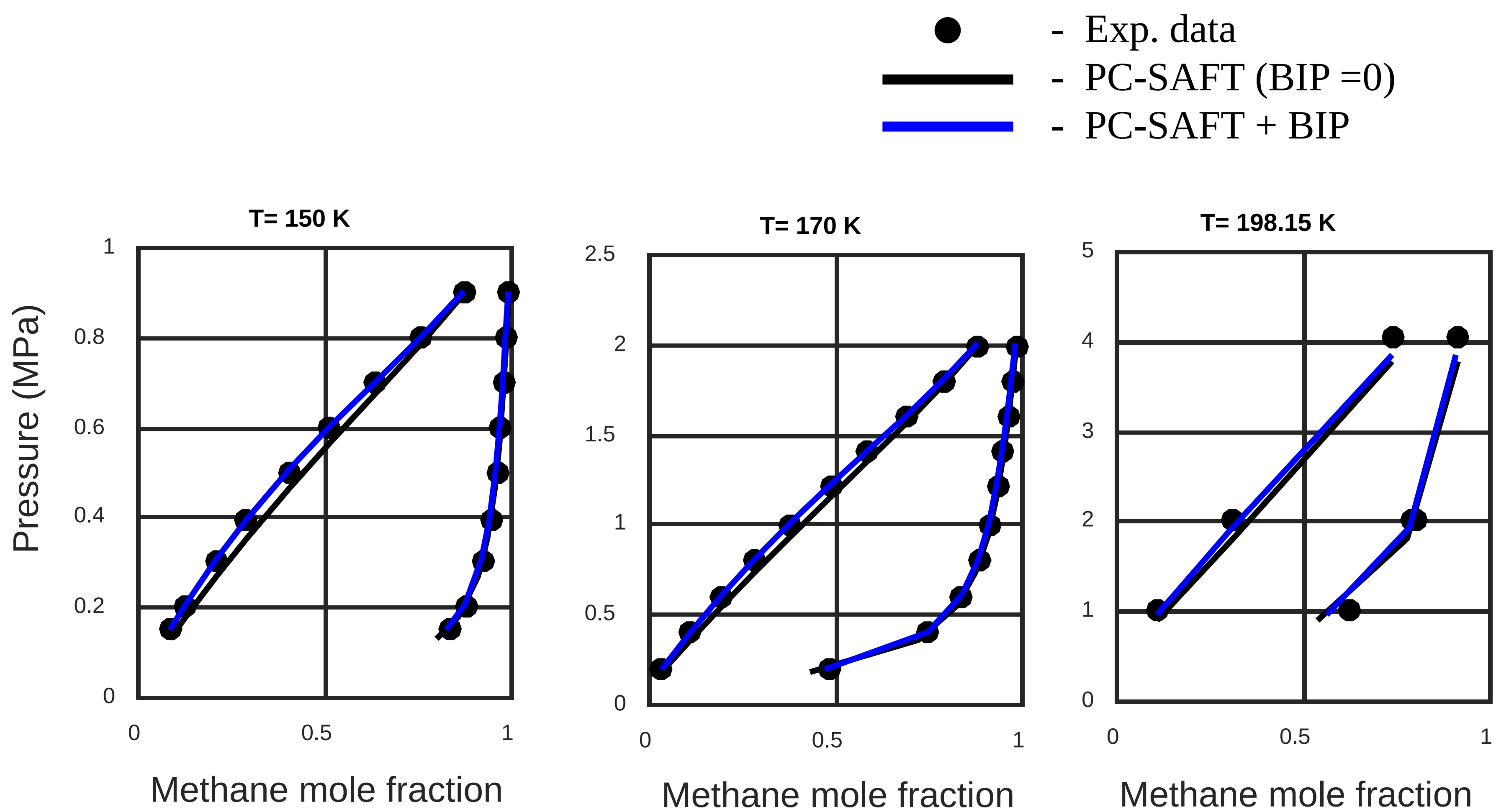
Ethylene mixtures with impurities



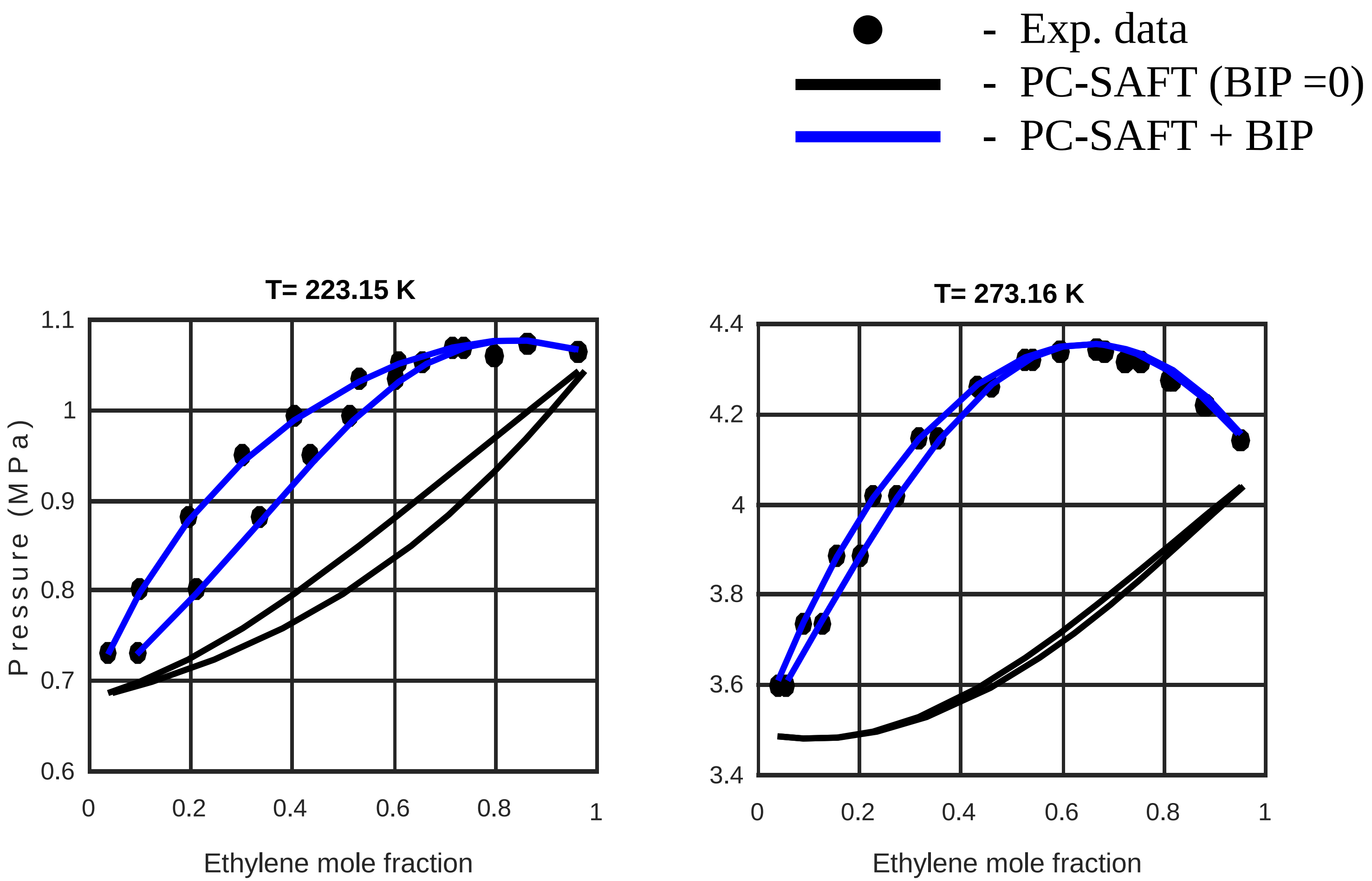
Possible impurities:

- Hydrogen
- Carbon Dioxide
- Methane
- Ethane
- Propane
- Propylene
- Butylene
- Butane
- Butadiene

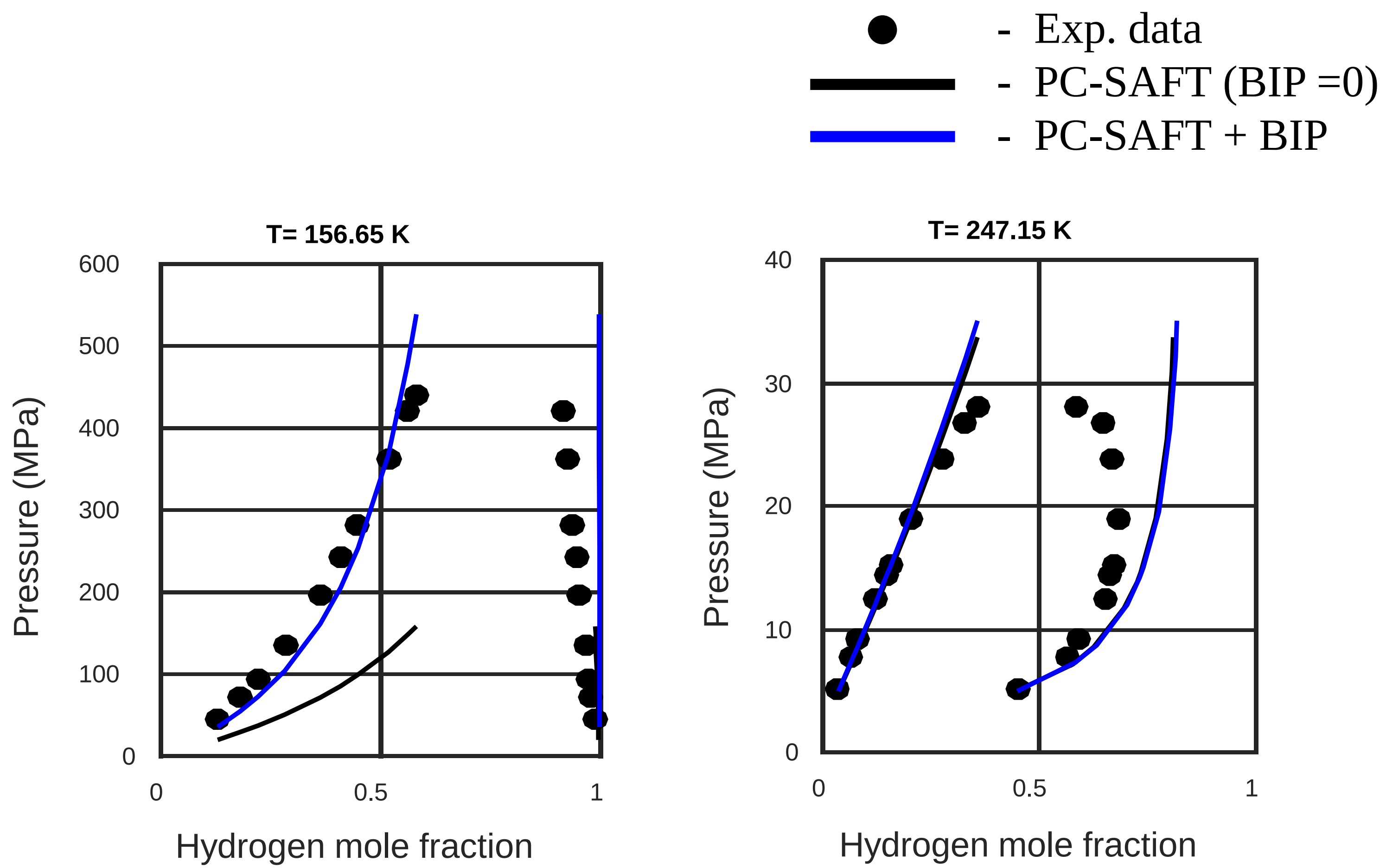
Ethylene – Methane VLE



Ethylene – Carbon Dioxide VLE



Ethylene – Hydrogen VLE



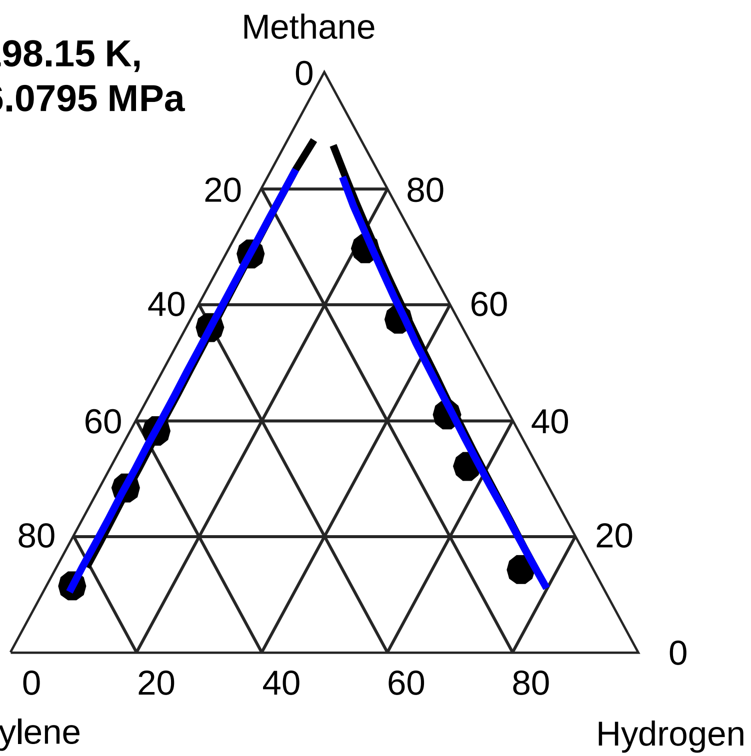
VLE in Ternary Mixtures

● - Exp. data

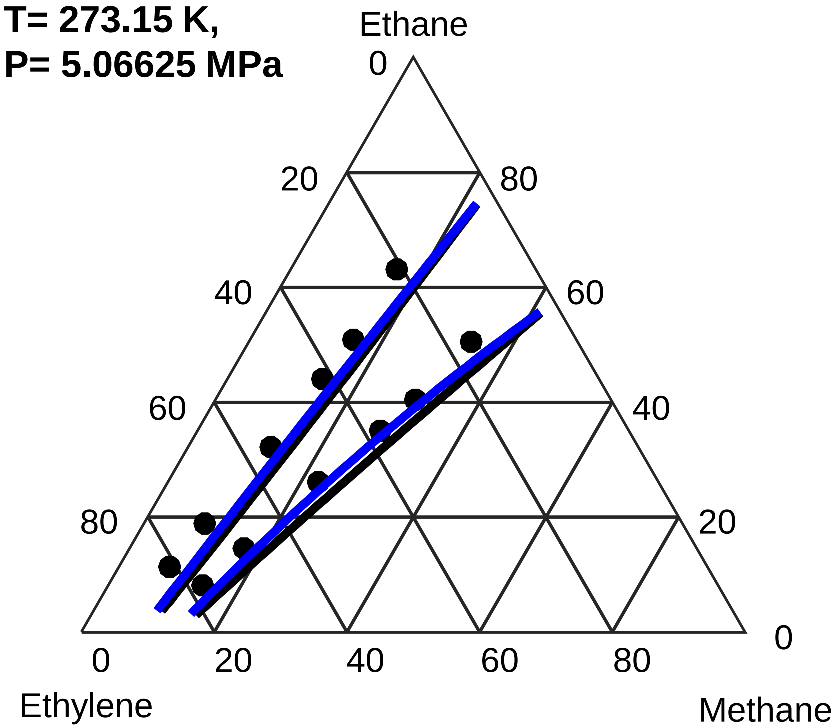
▬ - PC-SAFT (BIP =0)

▬ - PC-SAFT + BIP

T= 198.15 K,
P= 6.0795 MPa



T= 273.15 K,
P= 5.06625 MPa



Experimental setup (INERIS) – Summer 2017

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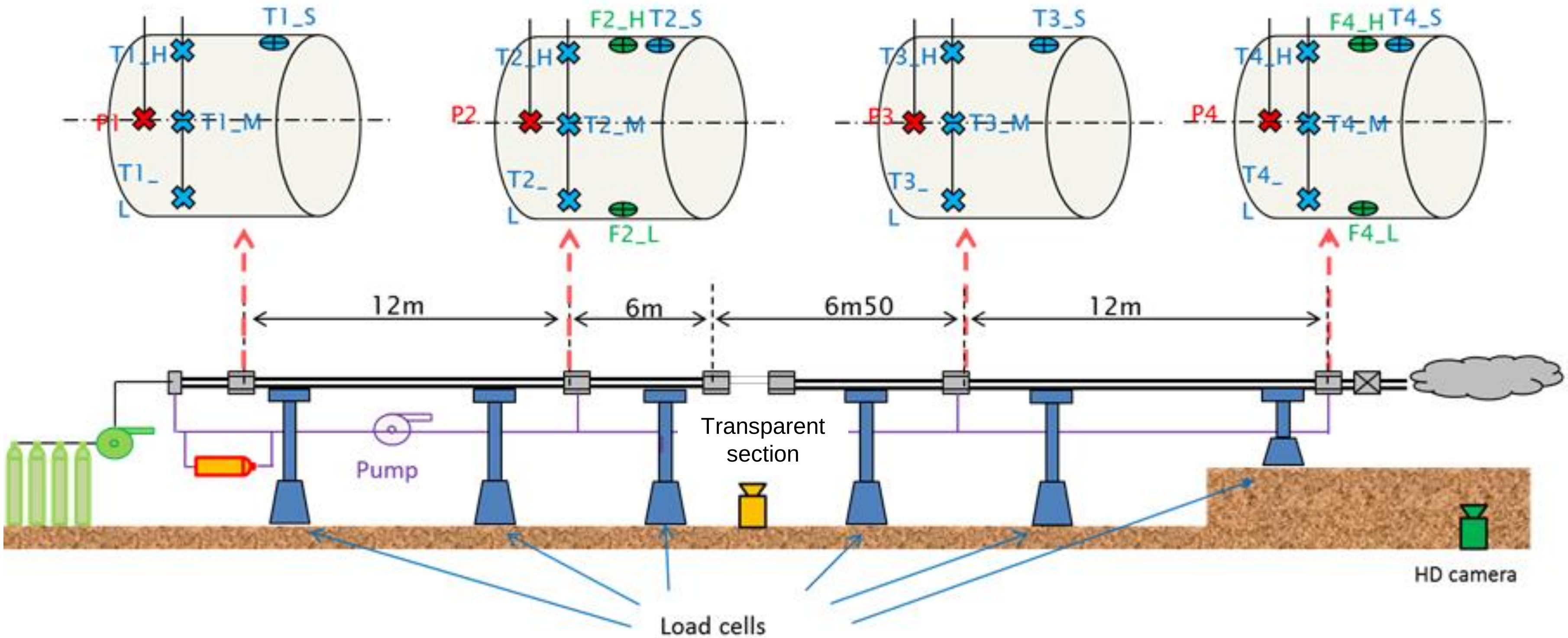
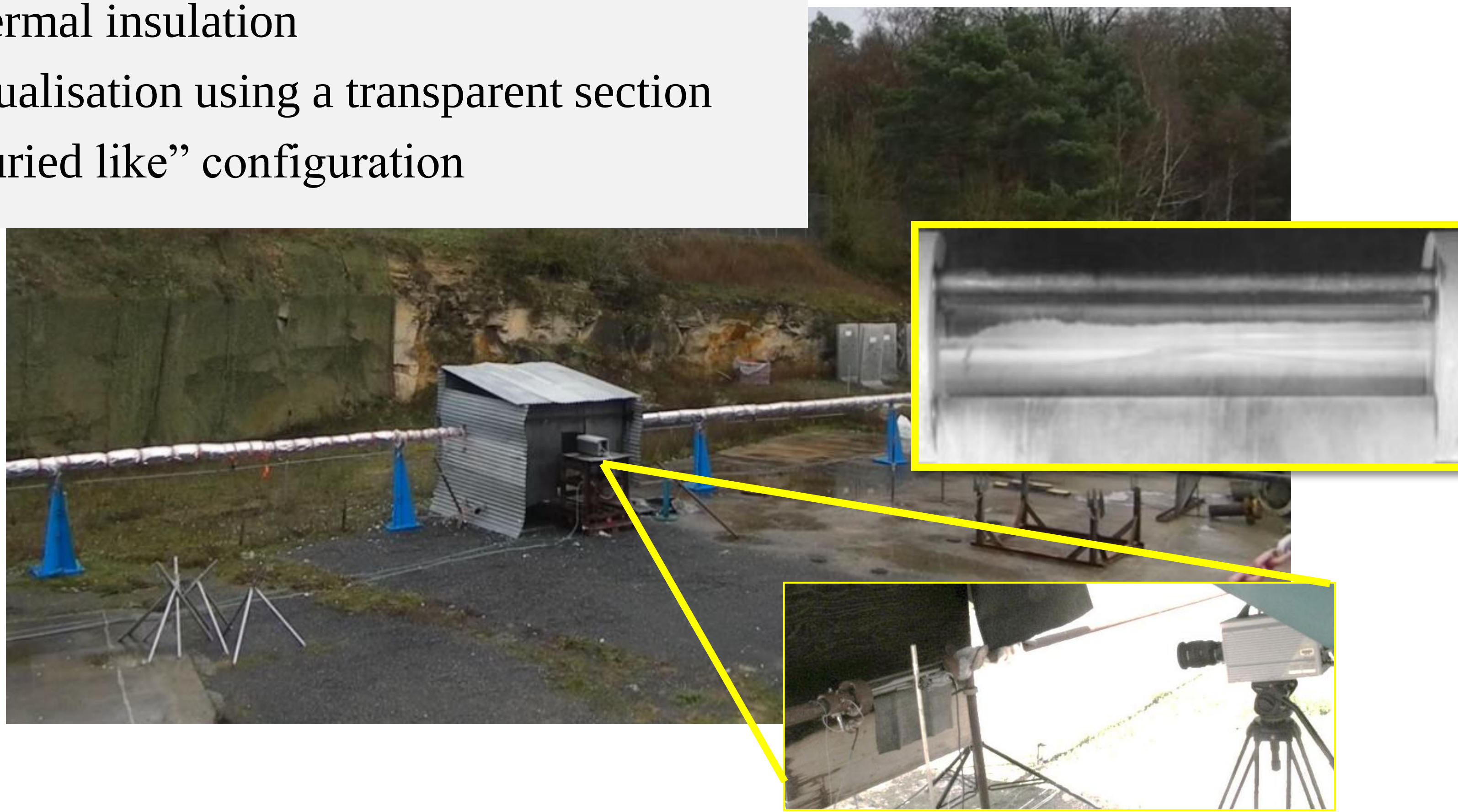


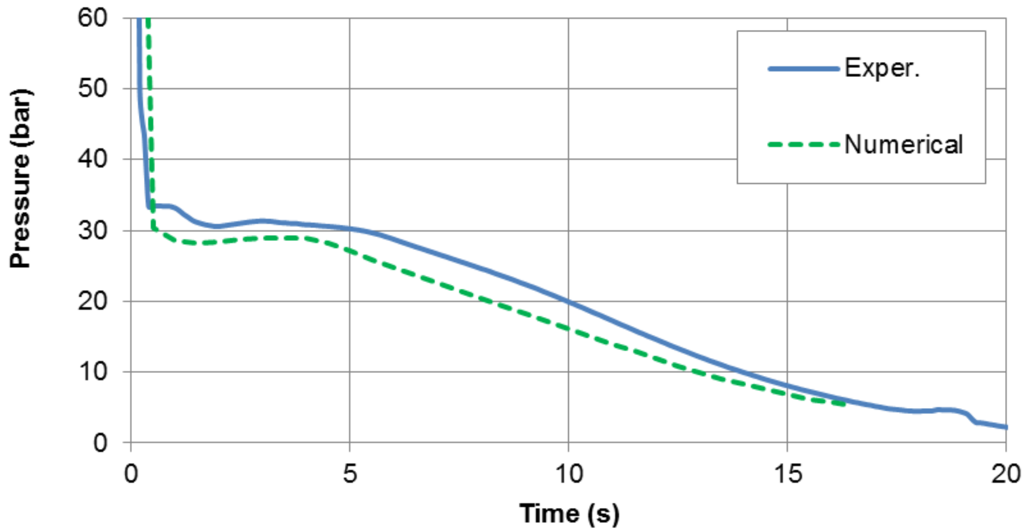
Schematic representation of the test pipeline (40 m long, 50mm i.d.), showing the ethylene feeding equipment, and the locations of the pressure, temperature and heat flux transducers along the pipe.

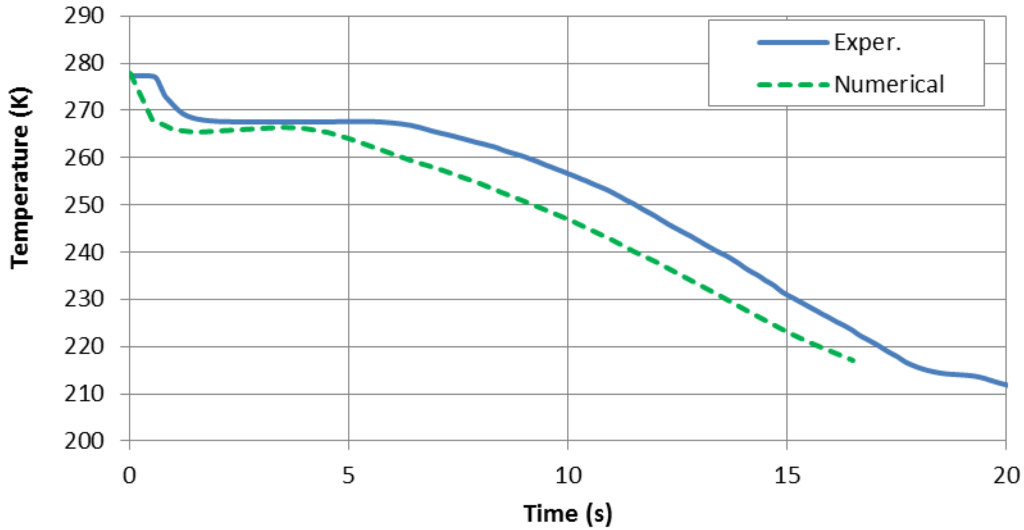
Experimental setup (INERIS)

- High pressure test pipeline (up to 70 bar)
- Heating system (T°~10-15°C)
- Thermal insulation
- Visualisation using a transparent section
- "Buried like" configuration



Example of FBR simulations





COOLTRANS

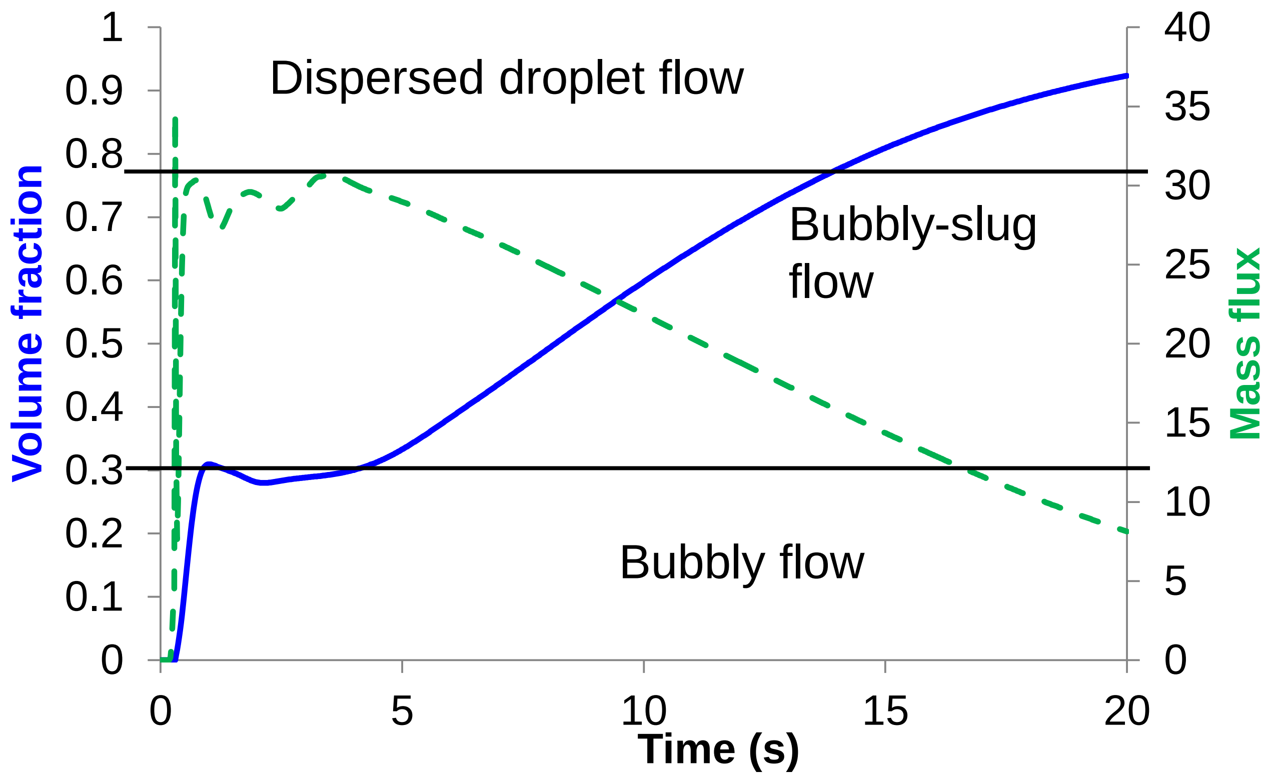
FBR test:

L = 144 m

D = 150 mm

Inventory: CO_2

Example of FBR simulations



FBR simulations – summary

- Homogeneous mixture flow model predicts well the measured pressure data, and can be recommended as a robust tool for the FBR consequence modelling, ESDV spacing and fracture propagation analysis,

- No validation data is available to quantify the effects of heat transfer and two-phase flow regime

Puncture simulations

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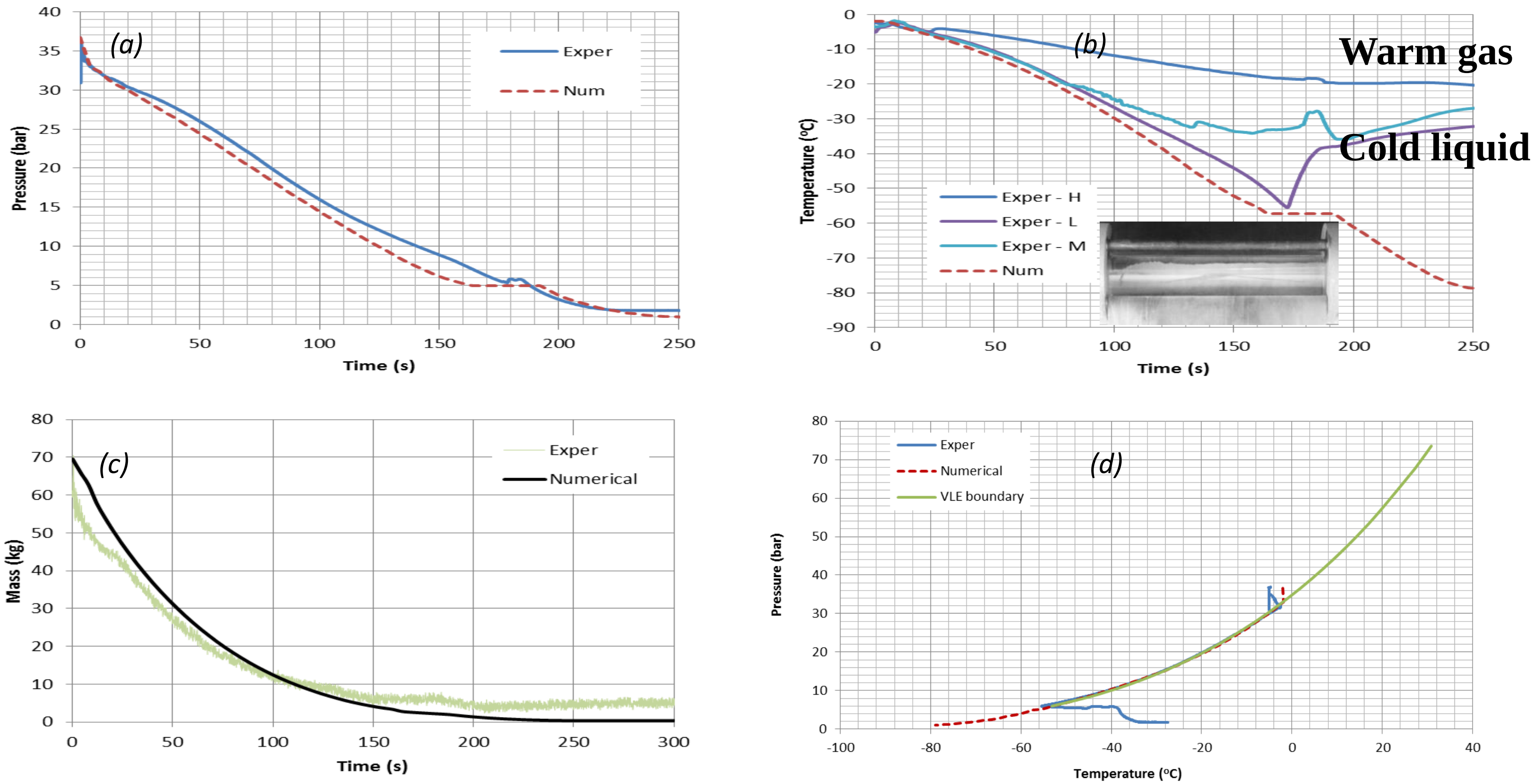


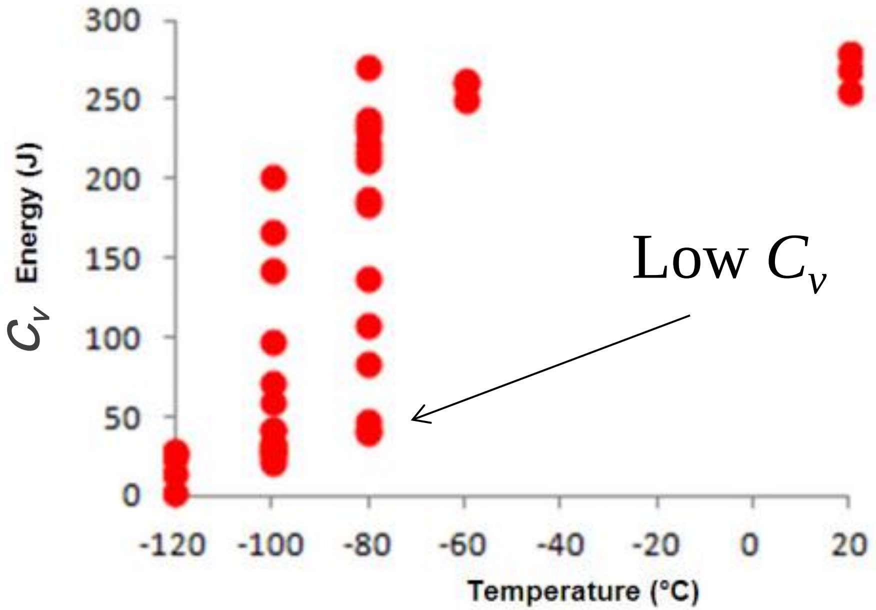
The history of variation of the fluid pressure *(a)*, temperature *(b)* and the pipeline inventory *(c)* as predicted by the flow model in comparison with the CO2QUEST data (INERIS puncture Test 14). *(d)* - pressure-temperature diagram showing the CO_2 vapor saturation line and the pipeline decompression trajectory

Puncture simulations – summary

- HEM fails to capture the effect of thermal stratification observed in the experiments,
- Accounting for the wall-fluid heat transfer is important to get agreement with the pressure and temperature measurements.

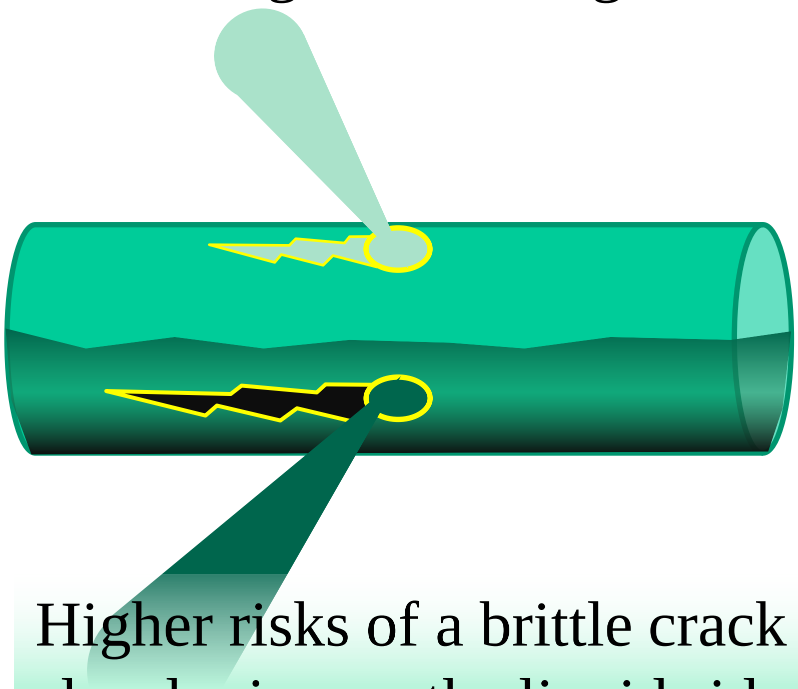
Implications of thermal stratification

Fracture toughness C_v determines the mode and speed of crack propagation; C_v is a strong function of temperature



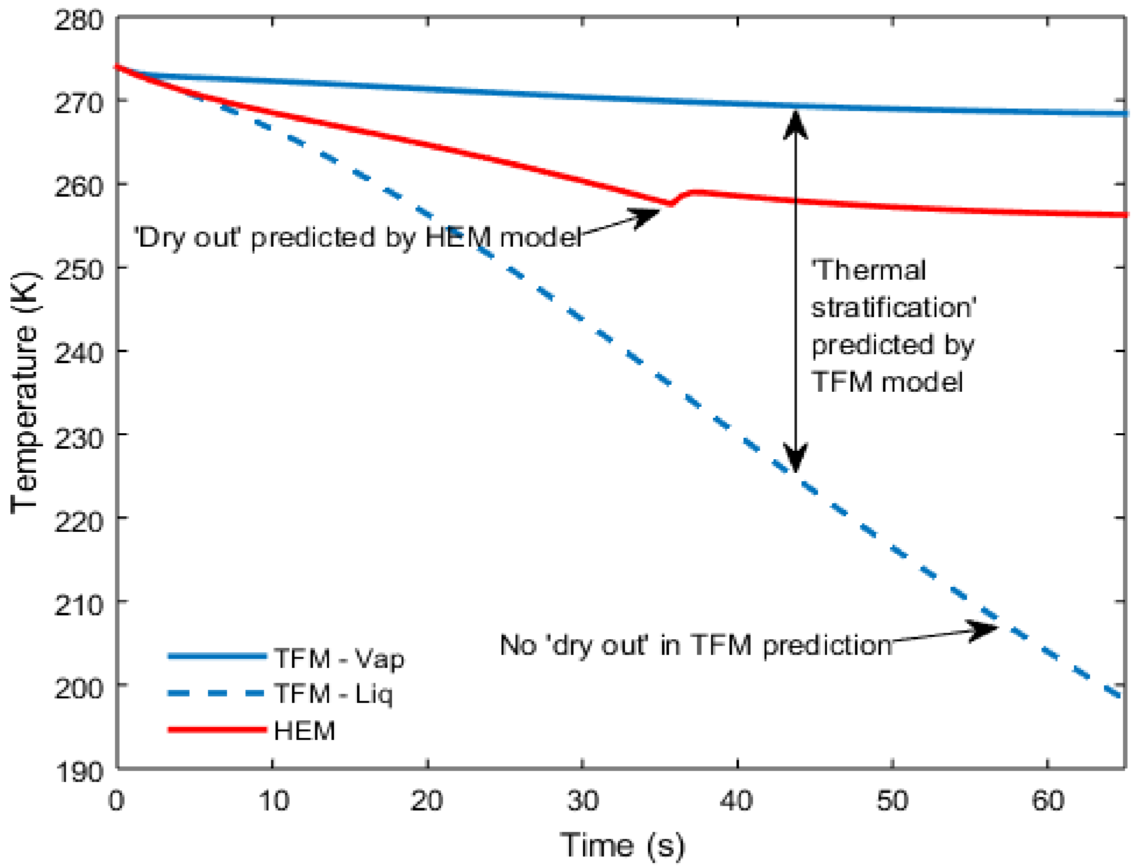
Charpy impact test energy for X70 grade steel

Pipeline side puncture leading to a running crack

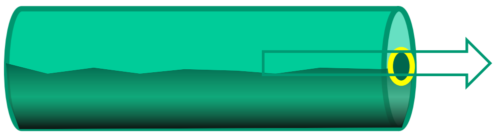


Higher risks of a brittle crack developing on the liquid side

Puncture simulations – Ethylene



Puncture at the end of a pipe



History of the fluid temperature variation in the pipeline near the rupture location. Predictions by HEM and TFM models. Pipe length 37m, pipe i.d. 50 mm, puncture diameter 12mm. Initially the fluid is saturated 50%v/v liquid at $0^{o}C$.

Conclusions and Future Work

- Development of a comprehensive simulation package
  - transient discharge flow models;
  - PC-SAFT model for ethylene and impurities
  - coupling using interpolation tables;
- Experimental work at INERIS (summer 2017) and model validation;
- Integration of the flow model with the consequence modelling and risk assessment tools;
- Demonstration of the efficacy of the models developed by their application to a realistic pipeline.

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The statements made herein are solely the responsibility of the authors.