Wrocław University of Technology

# Cryogenic Safety – HSE Seminar

## The numerical evaluation of the minimal outlet area of the safety valve in the pipelines of cryogenic installations

*Ziemowit M Malecha, Maciej Chorowski and Jaroslaw Polinski*

Department of Cryogenic, Aeronautic and Process Engineering
**Wroclaw University of Science and Technology**, Poland

# Motivation

- The flow of cold helium in pipes is a fundamental issue of any cryogenic installation
- Pipelines for helium transportation can reach lengths of hundreds of meters
- Emergency valves are among the most common safety devices located on the pipelines
- The proper selection of a size is a crucial part of the costs for the entire installation and its safe operation
- The size of the safety valve must be properly designed in order to avoid a dangerous pressure build-up
- The most commonly occurring dangerous situation is an undesired heat flux in the helium as a result of a broken insulation
- The heat flux can be intense and the build-up of the pressure in the pipe can be very rapid

# Aim and Scope

- Numerical evaluation of the build-up of pressure and temperature in the pipe, as a consequence of a sudden and intense heat flux.
- Evaluation of the proper size of a safety valve (minimal outlet area) in order to avoid a rise in pressure above a safety limit.
- Evaluation of the proper size of an individual pipe in order to avoid overestimation and any unnecessary increase in cost.
- Usage of the open source CFD toolbox – OpenFOAM.

# Motivation for 2D calculations

- **Necessity to predict the dynamics of the pressure increase** for each individual pipeline, and for the given heat flux – large number of calculations

- Zero dimensional analysis is limited and tends to be overestimated and is insufficient for the proper calculation of a size of a safety valve

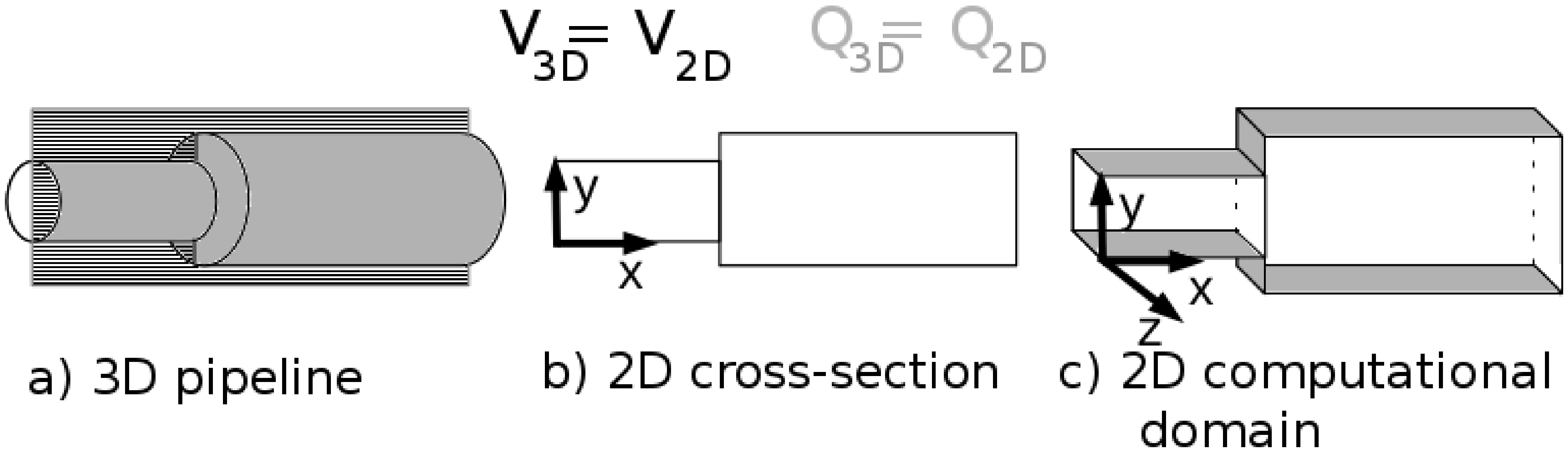
- 3D CFD analysis prohibitively long because each individual pipe is hundreds of meters long

- 2D calculations are orders of magnitude faster than their 3D originals
  **Difficulty:** transformation of 3D geometry to its 2D numerical representation

- **Minimal mathematical model**: to calculate the dynamics of cryogenics gases: Navier-Stokes, ideal gas, additive mixing – Confirmed by comparison with experiment

# Transformation of the 3D geometry to its 2D representation

- Long and thin geometry: flow is invariant in width direction, $\partial()/\partial z = 0$




**To preserve the flow and thermal similarities:**

- The volume of the original pipeline and its numerical model are equal, $V_{3D} = V_{2D}$.
- The total heat delivered through the walls is the same for the original pipeline and the numerical model, $Q_{3D} = Q_{2D}$, where: $Q_{3D} = q_{3D} A_{3D}$ and $Q_{2D} = q_{2D} A_{2D}$ .
- The cross-section of the emergency valves is the same for the original pipeline and its numerical model, $A_{Ve3D} = A_{Ve2D}$.
- Numerical geometry has 3 dimensions (length, height and width).
- Area of the walls of the 3D pipeline is not equal to the area of the walls of the 2D computational domain. $A_{3D} \neq A_{2D}$.

# Mathematical model and numerical implementation

OpenFOAM (Open Source Field Operation and Manipulation) CFD toolbox

- **E**ffectively used in diverse and challenging applications
- Compared with analytical solutions and experimental data

***SonicFOAM*** solves for a transient, trans-sonic/supersonic flow of a compressible gas:

- high speeds are expected
- the sudden opening of an emergency valve can cause the creation of a shock wave
- numerical schemes that can capture these features while avoiding spurious oscillations

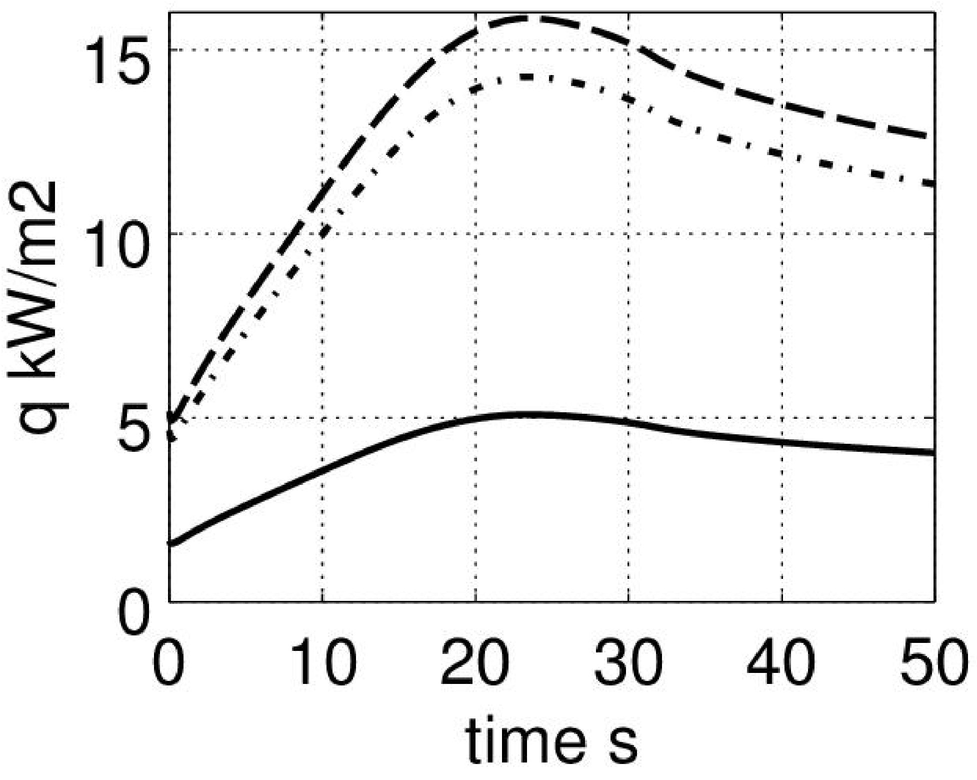
Finite volume discretization and the PISO (Pressure Implicit with Splitting of Operators)

$$\frac{\partial \rho \boldsymbol{u}}{\partial t}+\nabla\cdot(\rho \boldsymbol{u}\boldsymbol{u})=-\nabla p+\nabla\cdot(\mu\nabla \boldsymbol{u}) \qquad \boldsymbol{u}=(u,v,w)$$

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho \boldsymbol{u})=0 \qquad \rho=\frac{p}{rT}$$

$$\frac{\partial \rho e}{\partial t}+\nabla\cdot(\rho \boldsymbol{u} e)=\nabla\cdot\left(\frac{k}{C_v}\nabla e\right)+p\nabla\cdot \boldsymbol{u} \qquad e=C_v T$$

# Computational example 1: Pipeline with one change of diameter




Solid line – predicted heat flux in case of insulation failure

Dashed line – recalculated heat flux for the 1st example

Dash-dotted line – recalculated heat flux for the 2nd example

**The pipeline:**

- Two sections:

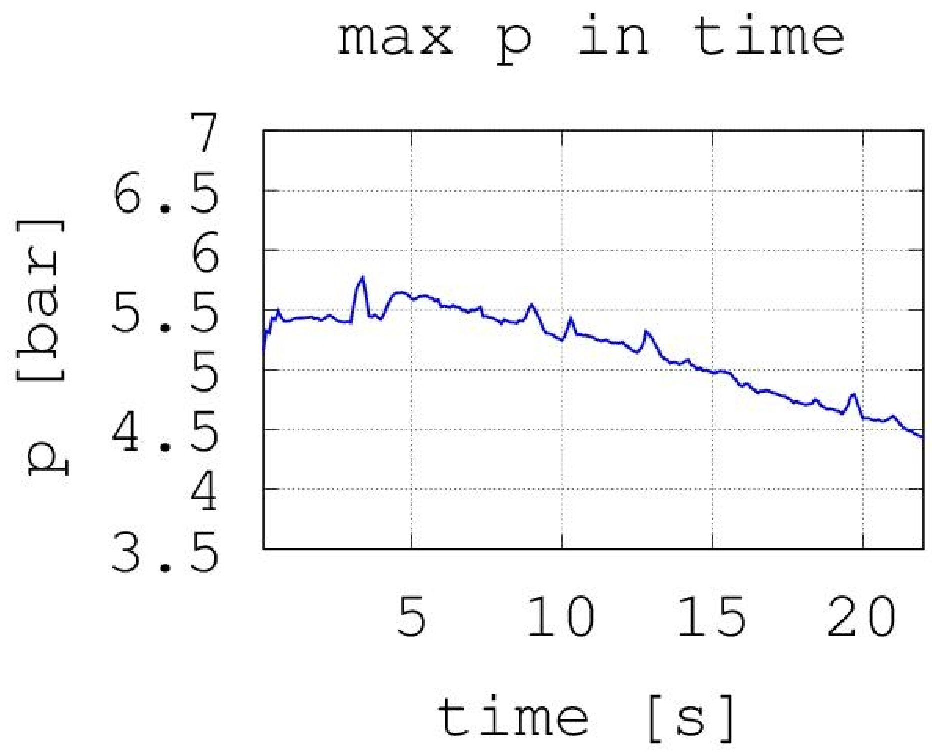
  $L_1 = 355\,m,\ d_1 = 72.1\,mm \quad L_2 = 55\,m,\ d_2 = 38.4\,mm$

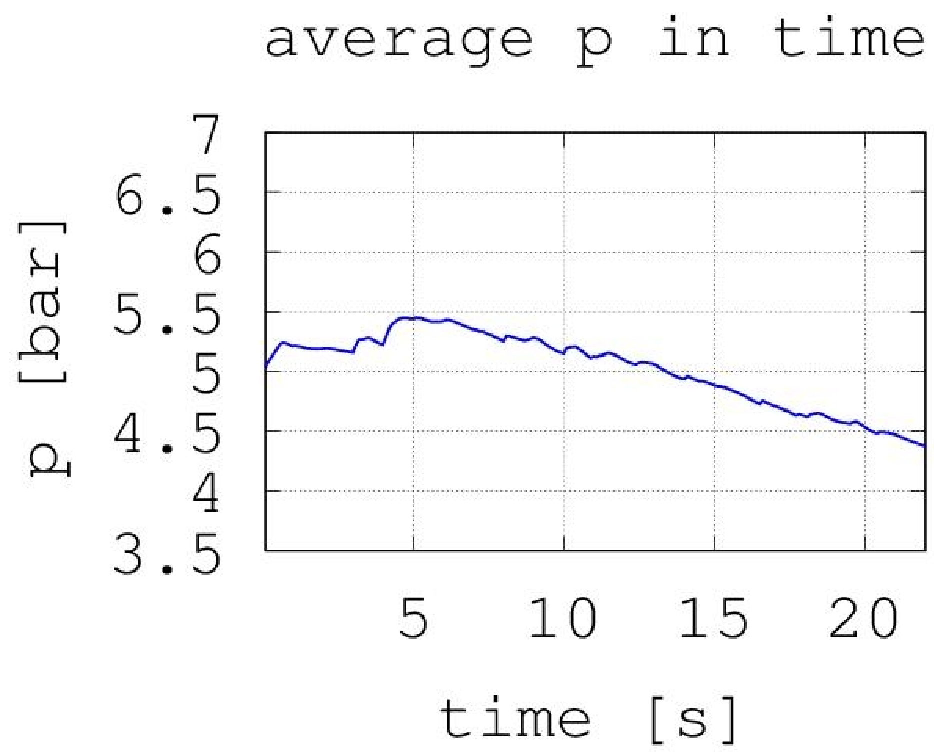
- The nominal pressure of the pipeline: 4 bar
- The maximum pressure allowed in the pipeline: 6 bar
- The emergency valves opens: 5 bar

**Initial conditions:**

- uniform pressure 5 bar
- two open emergency valves

**Trail and error procedure** to reach the desired flow condition: pressure below 6 bar




Pressure build-up in time for the pipeline equipped with emergency valves with minimal required diameters.

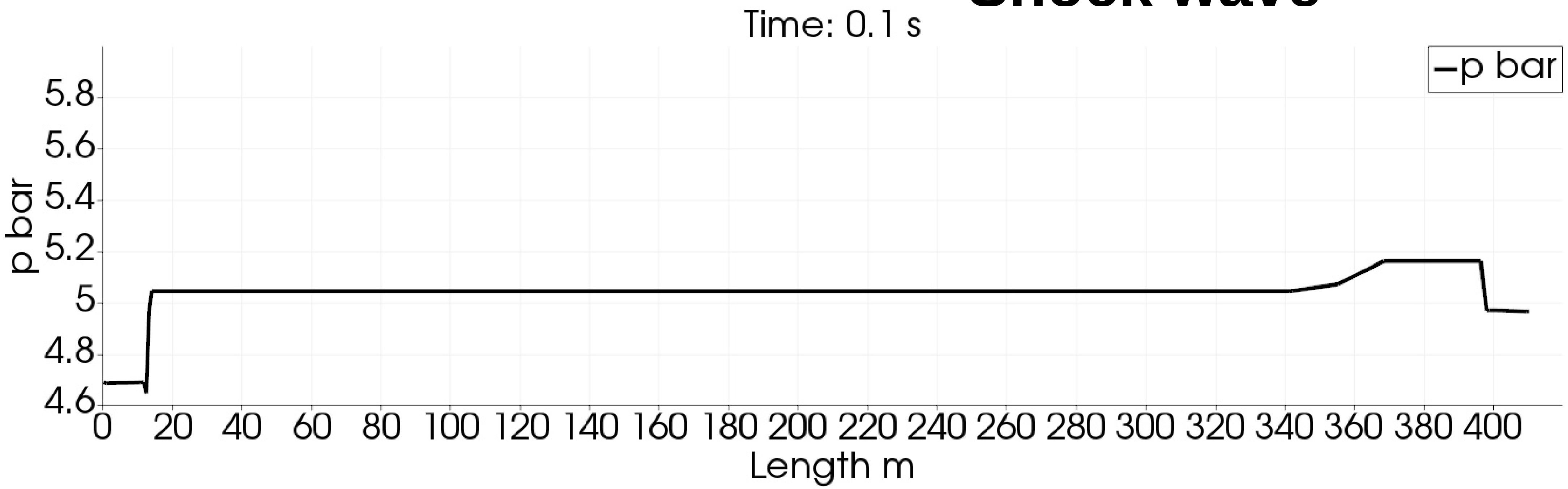
**Left plot**: the maximum pressure in time

**Right plot**: the average pressure in time

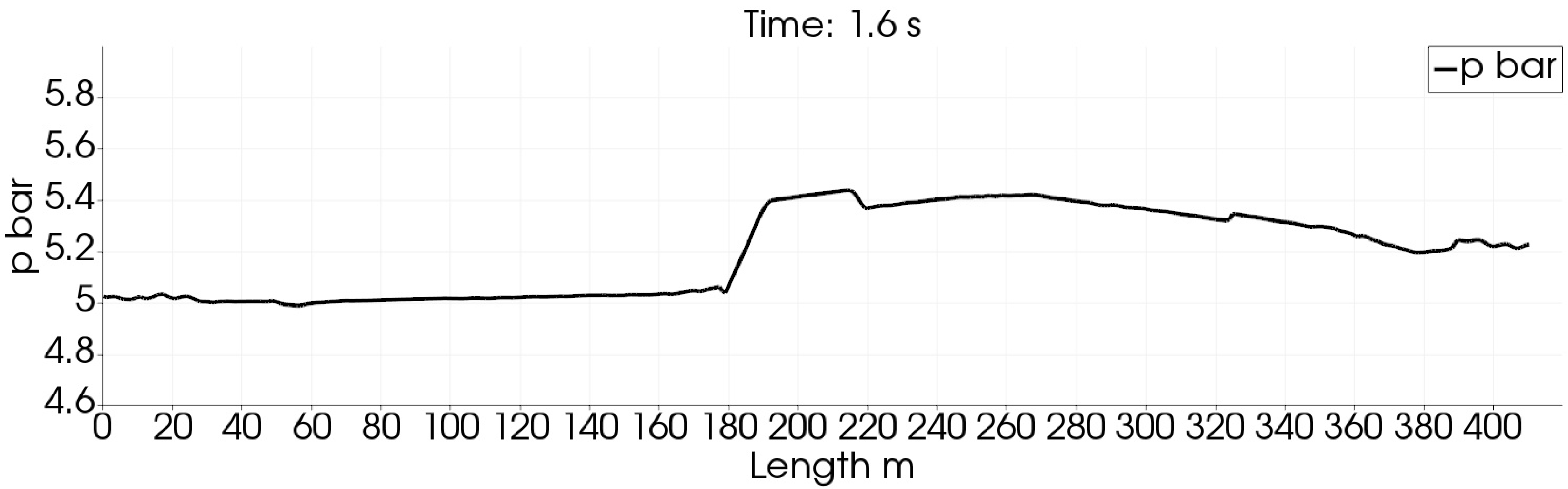
**The minimal diameter of the emergency valves:** $d_{v1} = 60.3\,mm,\ d_{v2} = 32.1\,mm$

Jet contraction effect included by reduction the useful diameter of the safety valve by 30%.

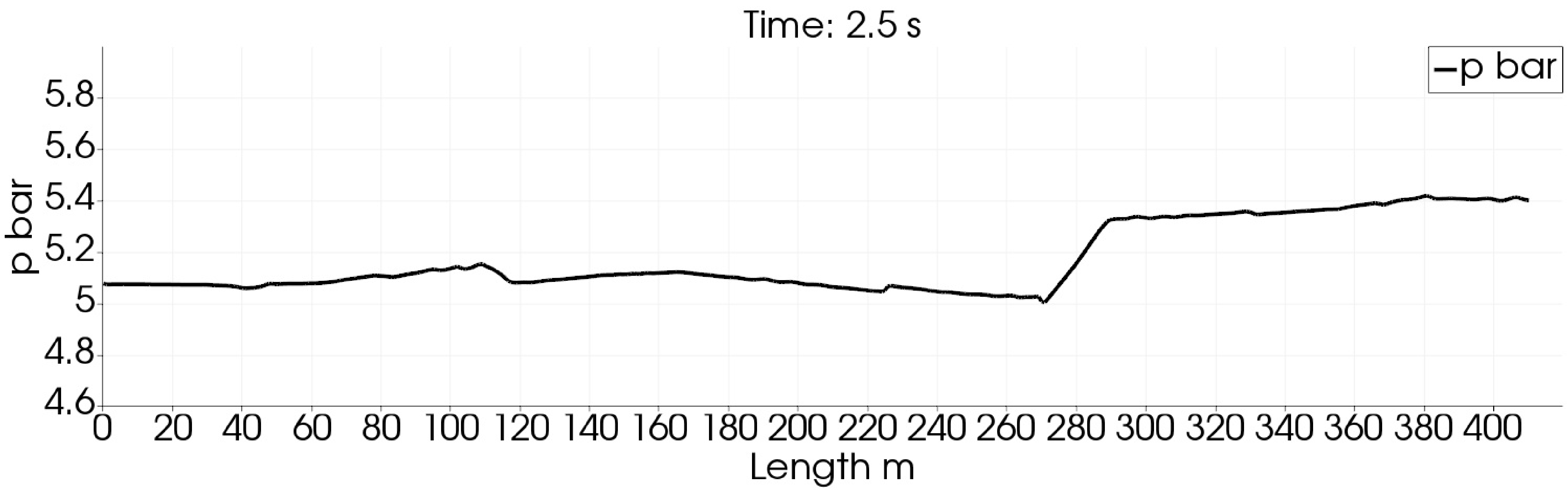
# Shock wave



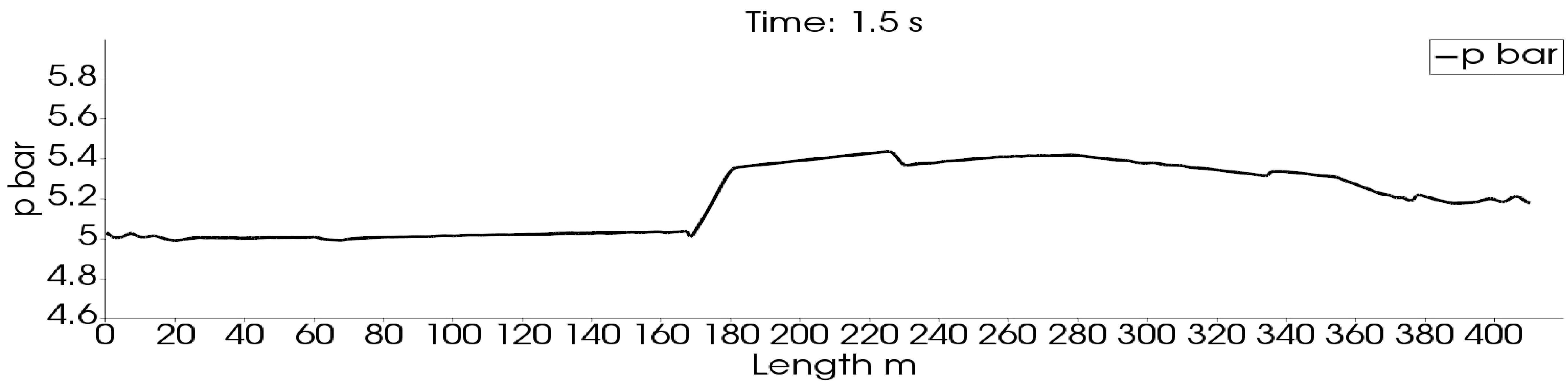

**Sudden opening** of the safety vales causes the shock waves to be created at both ends of the pipeline.



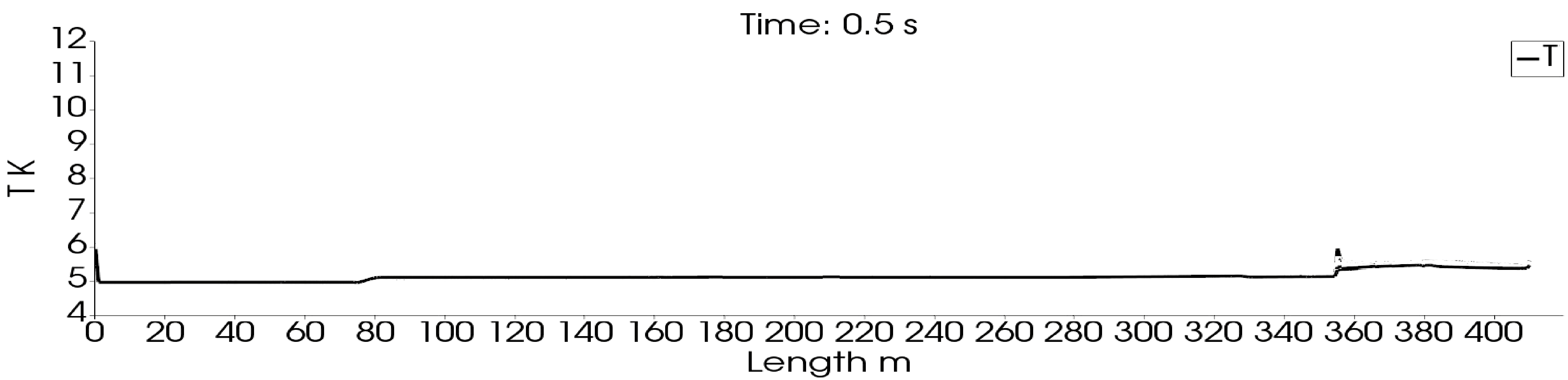

The waves travel along the pipeline, collide, and then travel backwards.



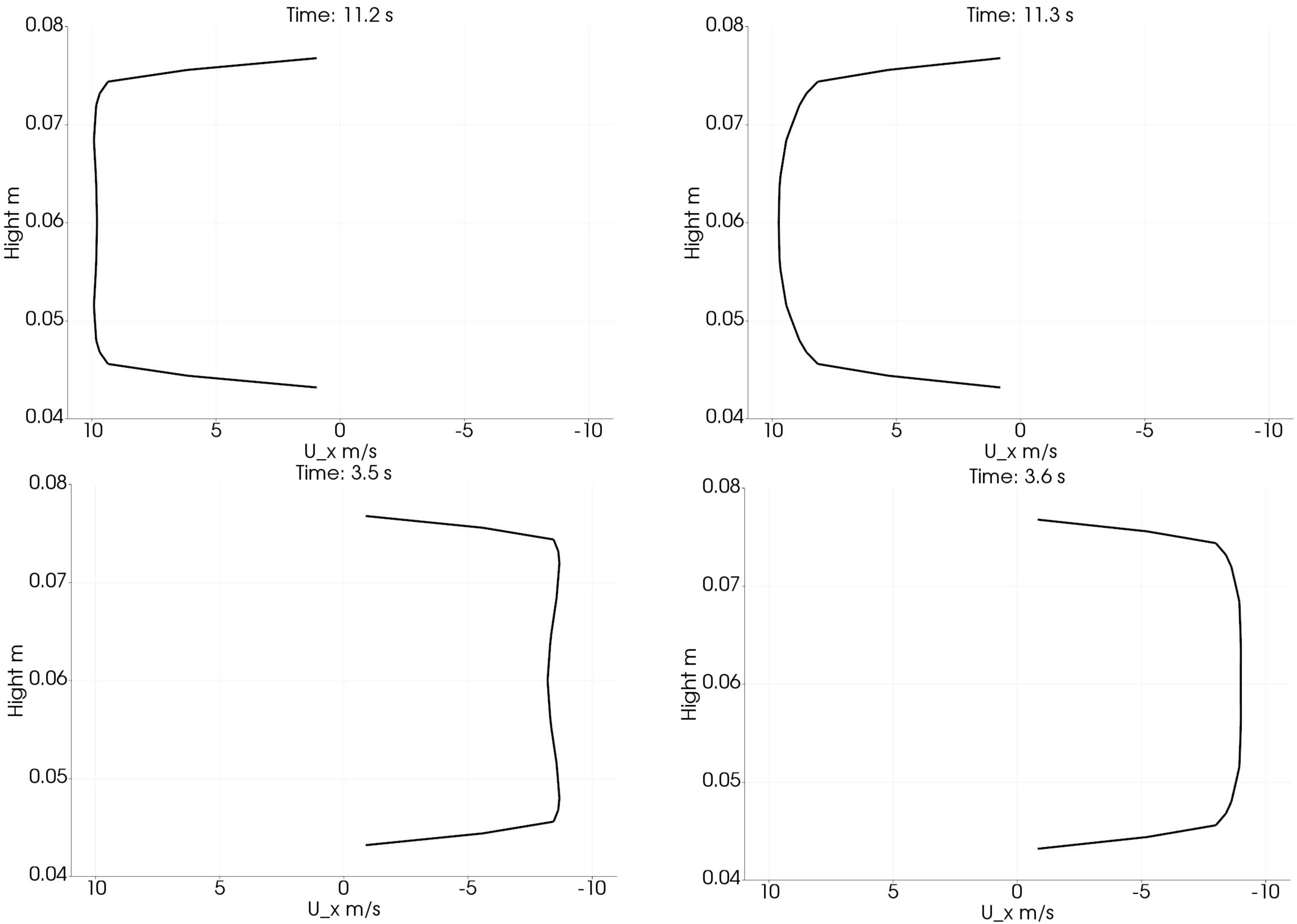

After 5 s, the waves flattened and after 15 s, the pressure went below 5 bar.



Time: 1.5 s
p bar
5.8
5.6
5.4
5.2
5
4.8
4.6
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Length m

Time: 0.5 s
T
T K
12
11
10
9
8
7
6
5
4
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
Length m




Change of the x component of velocity vector across the pipeline, at x = 30 m, u(x = 30, y).
Maximum velocity is ≈ 10 m/s.

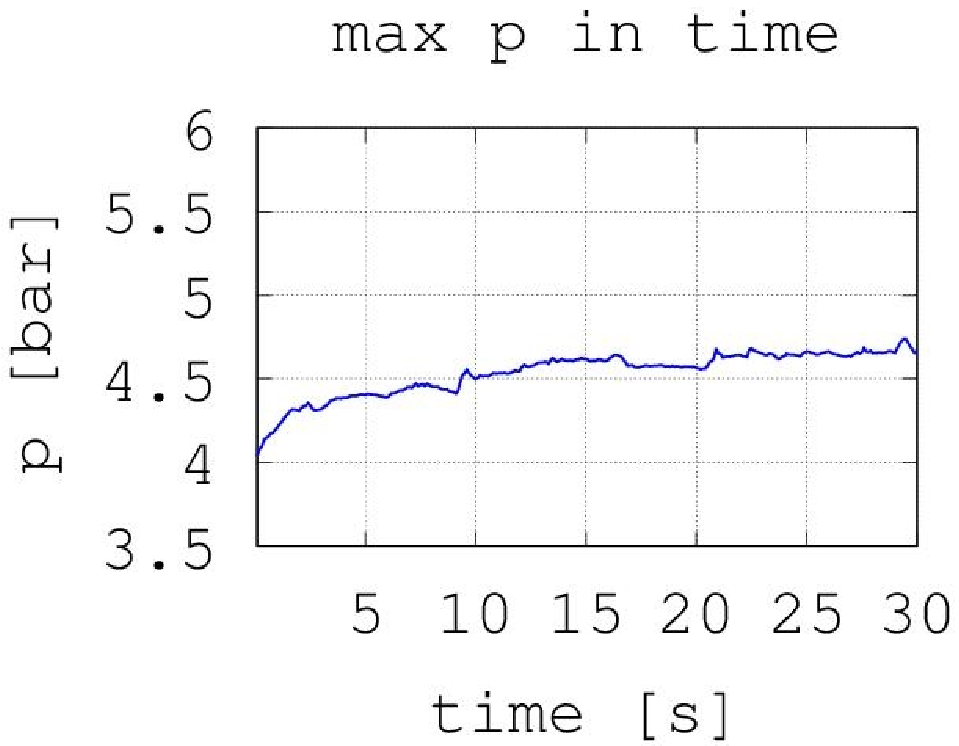
# Computational example 2: Pipeline with 2 changes of diameter

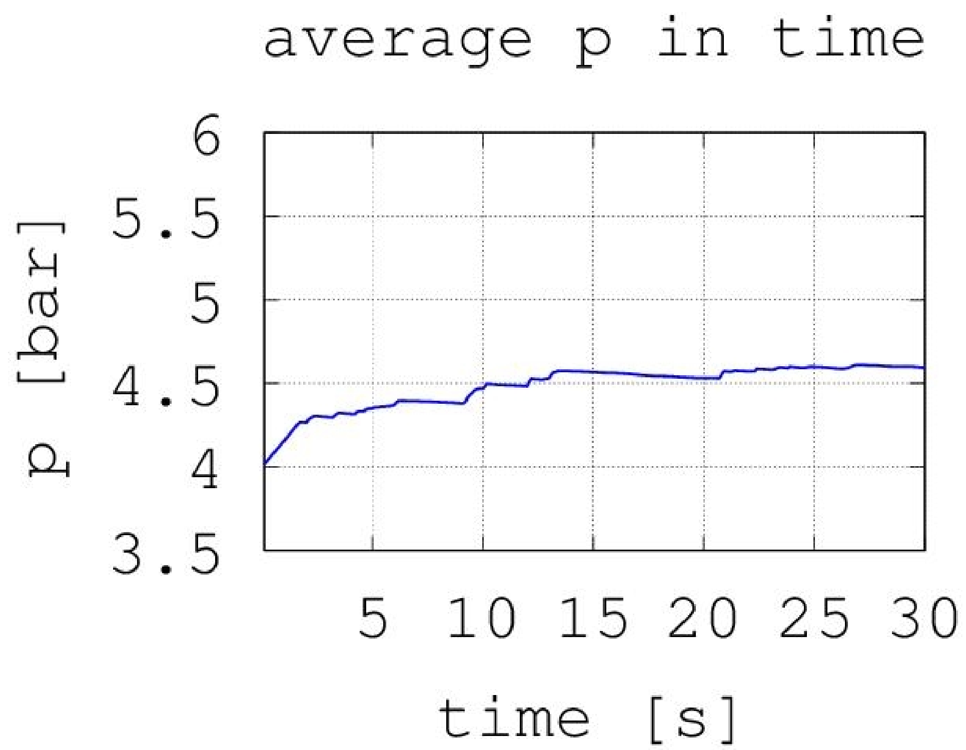
**The pipeline:**

- Three sections: $L_1 = 88\,m,\ d_1 = 267\,mm$
  $L_2 = 255\,m,\ d_2 = 214\,mm \quad L_3 = 55\,m,\ d_3 = 135\,mm$
- The nominal pressure of the pipeline: 3 bar
- The maximum pressure allowed in the pipeline: 4.75 bar
- The emergency valves opens: 4 bar

**Initial conditions:**

- uniform pressure 4 bar
- 2 open emergency valves




Pressure build-up in time for the pipeline equipped with 2 emergency valves: $d_v = 14\,mm$

- pressure never rises above 4.75 bar
- Opposite to the previous case, the pressure remains high for a longer time (wide plateau).
- After 42 s $p_{max}$ drops below 4.5 bar (not shown in the figure).

# Conclusions

- Generic approach for the evaluation of sizes of pipelines and emergency valves of a cryogenic installation.

- Consistent transformation of 3D geometry into simplified numerical geometry, in order to solve the problem using the appropriate 2D mathematical model.

- 2D numerical calculations are much faster when compared to their 3D originals, and much more accurate and informative when compared to the zero- or one-dimensional model.

- The proposed transformation keeps the geometrical and flow similarities (preserving the characteristic numbers: Reynolds number, Peclet number, Grashof number).

- Tool to help with the design process of any cryogenic installation (main benefits: fast calculation time, geometrical flexibility, possibility to use more complex mathematical models).

- Possible cost reduction related to the overestimation of the sizes of the pipelines and safety valves.