Experimental and numerical simulation of restarting flow of gelled crude oil.

Multiphase 2017 – ENS Paris-Saclay (Cachan, France)

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Wax is the challenge!

- What is wax?
- Wax is…
- …something you know:

(one particular form of wax, however…)

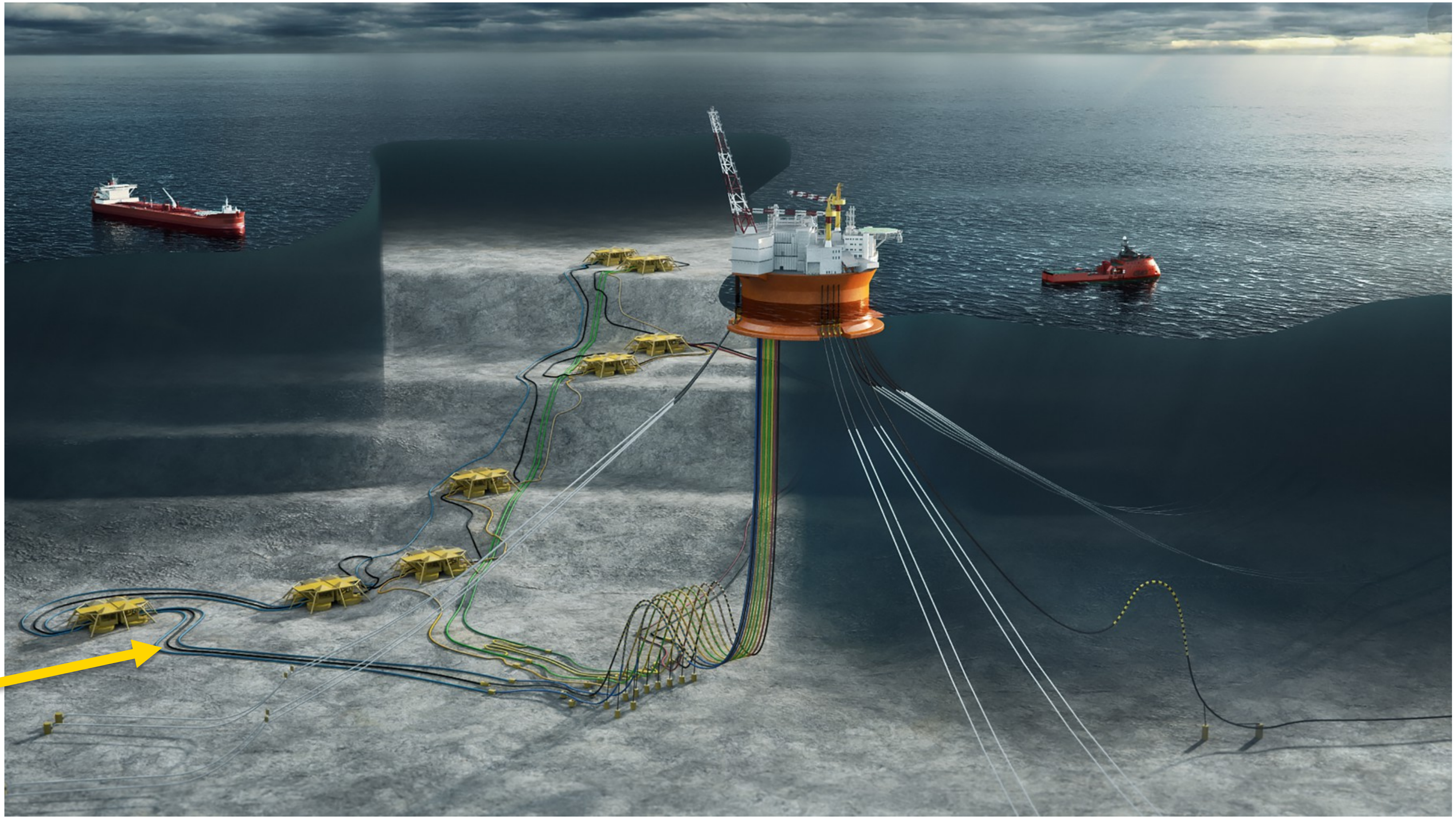
Foto: https://en.wikipedia.org/wiki/Candle

Where may we find wax?

- In every cold or subsea development there is RISK of wax deposition

- This risk must be taken into account during equipment design

(e.g. in pipelines)



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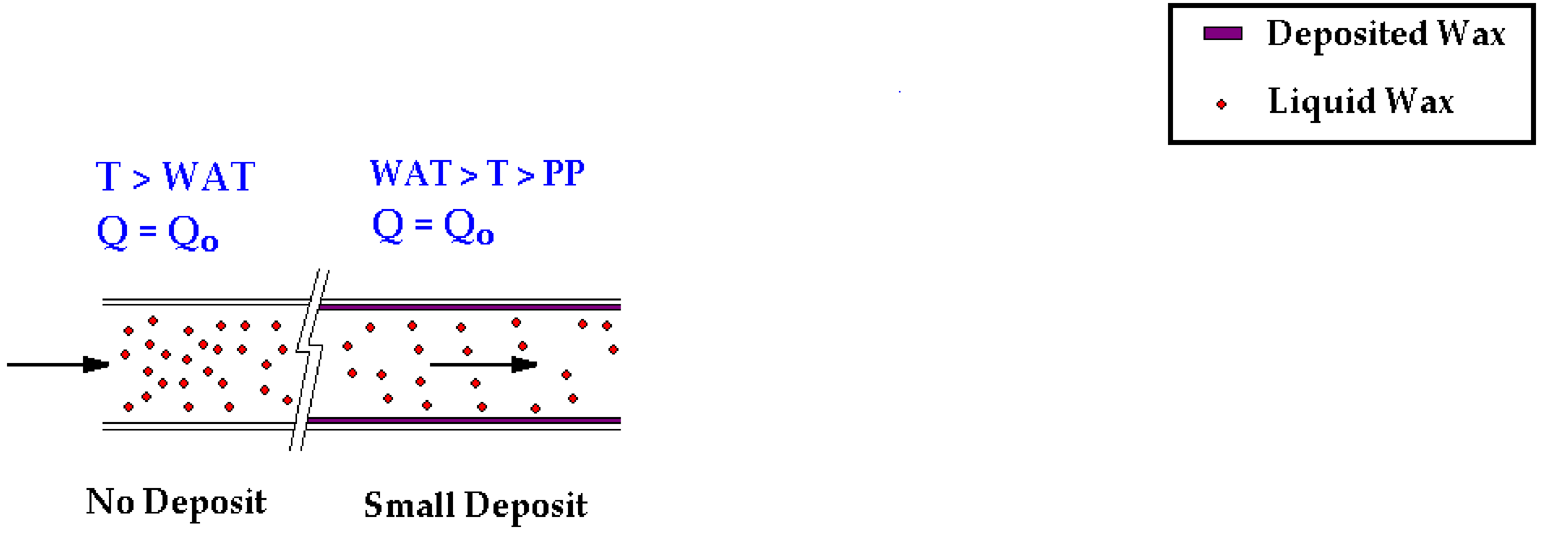

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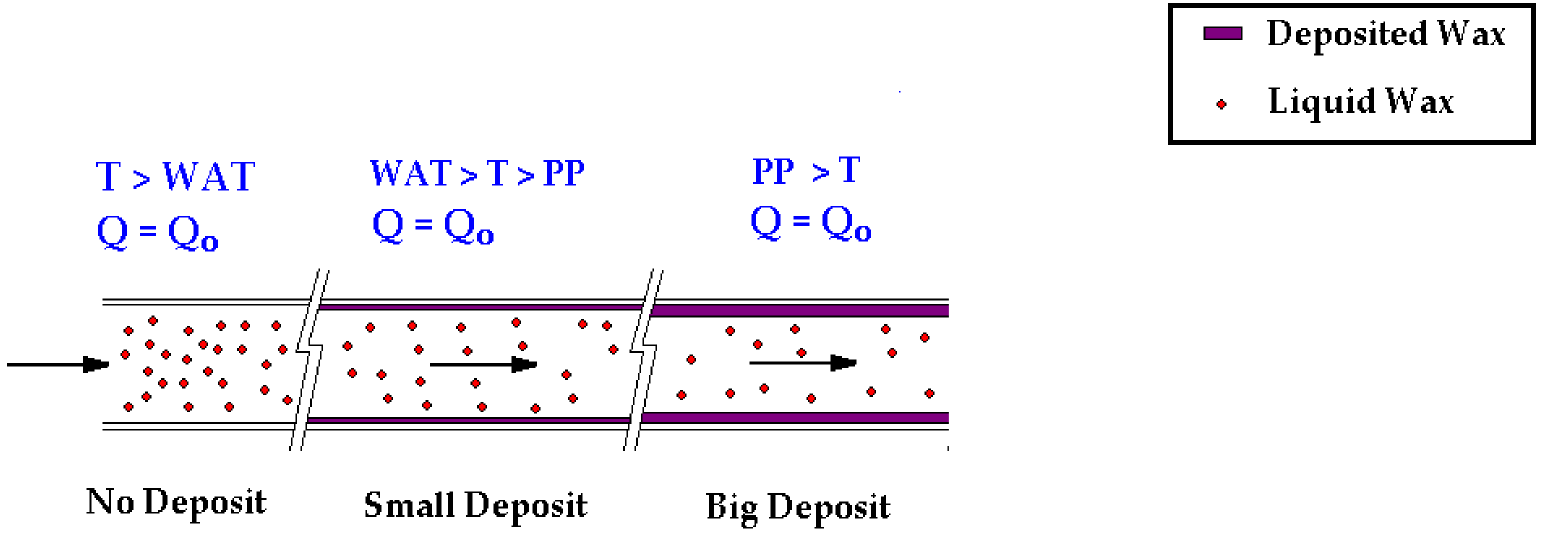
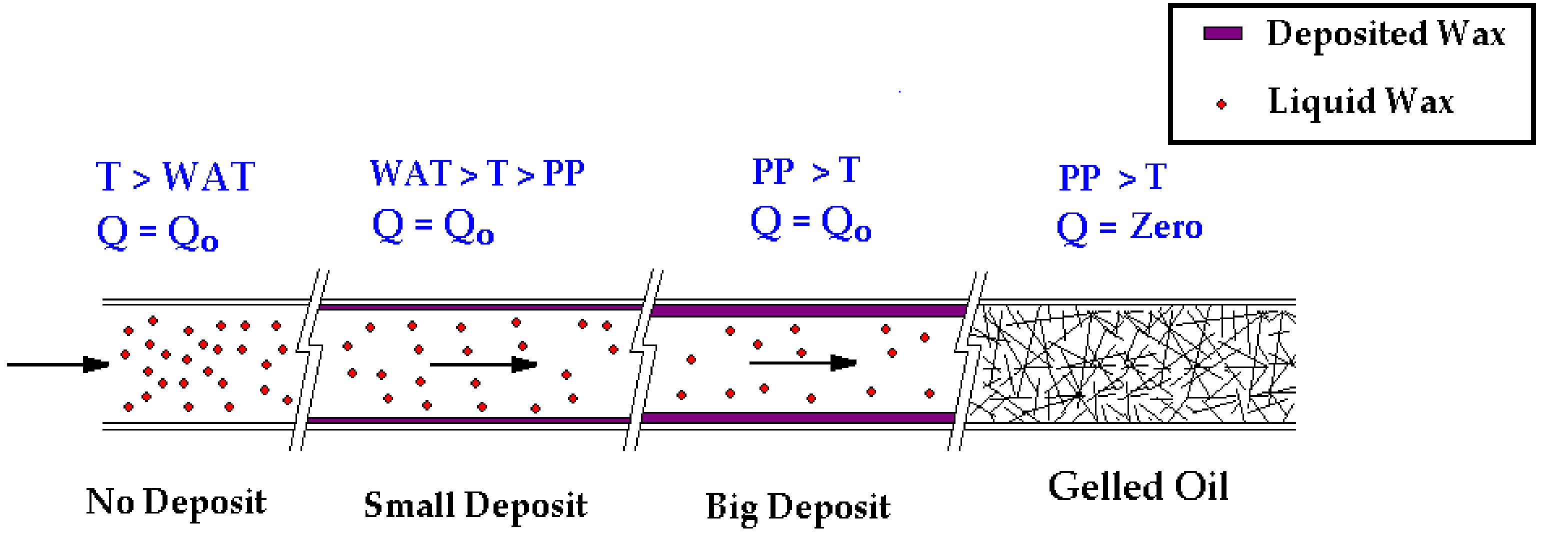


What happens in the pipeline transporting waxy crudes?

- Crude oil flows into the pipeline, temperature is high.
- Pipeline is cooled by the sea, temperature lower than WAT.
- Wax precipitates and may deposit on pipe inner wall.
- Eventually the fluid forms a gel and flow is blocked.



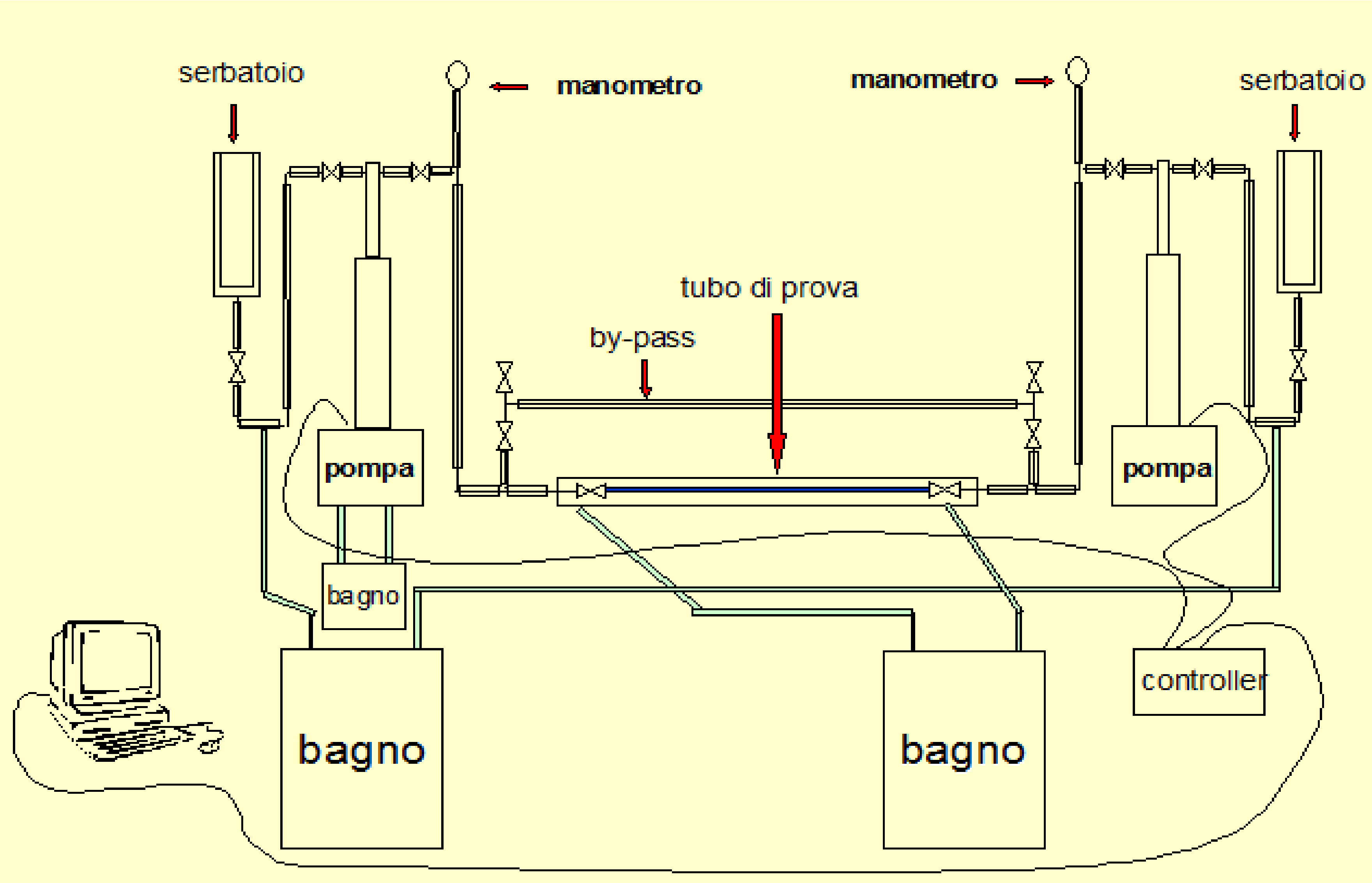
How to study wax?

Move to controlled settings. Go to the lab…

The lab.

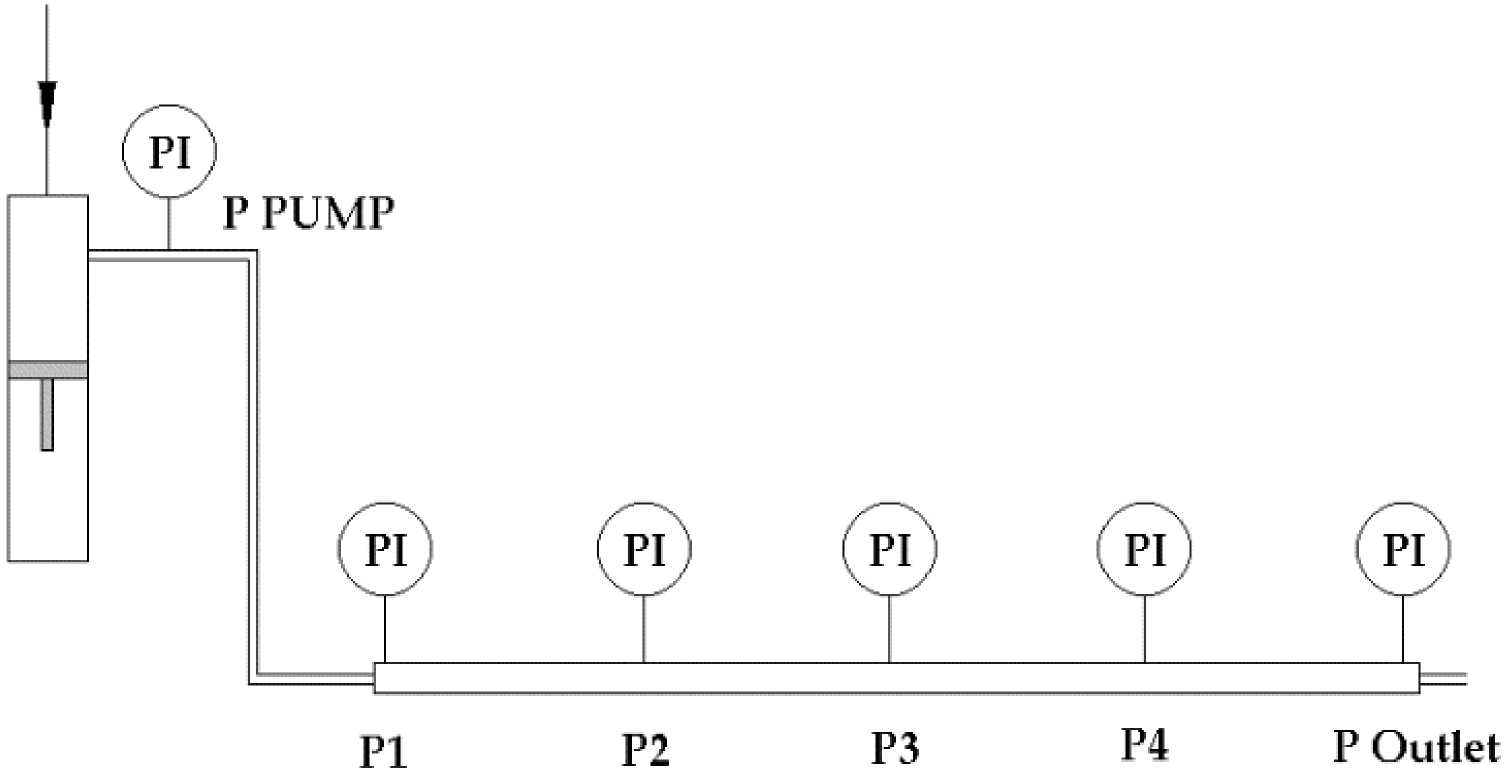
A picture from one of our lab buildings.

The lab – sketch of apparatus



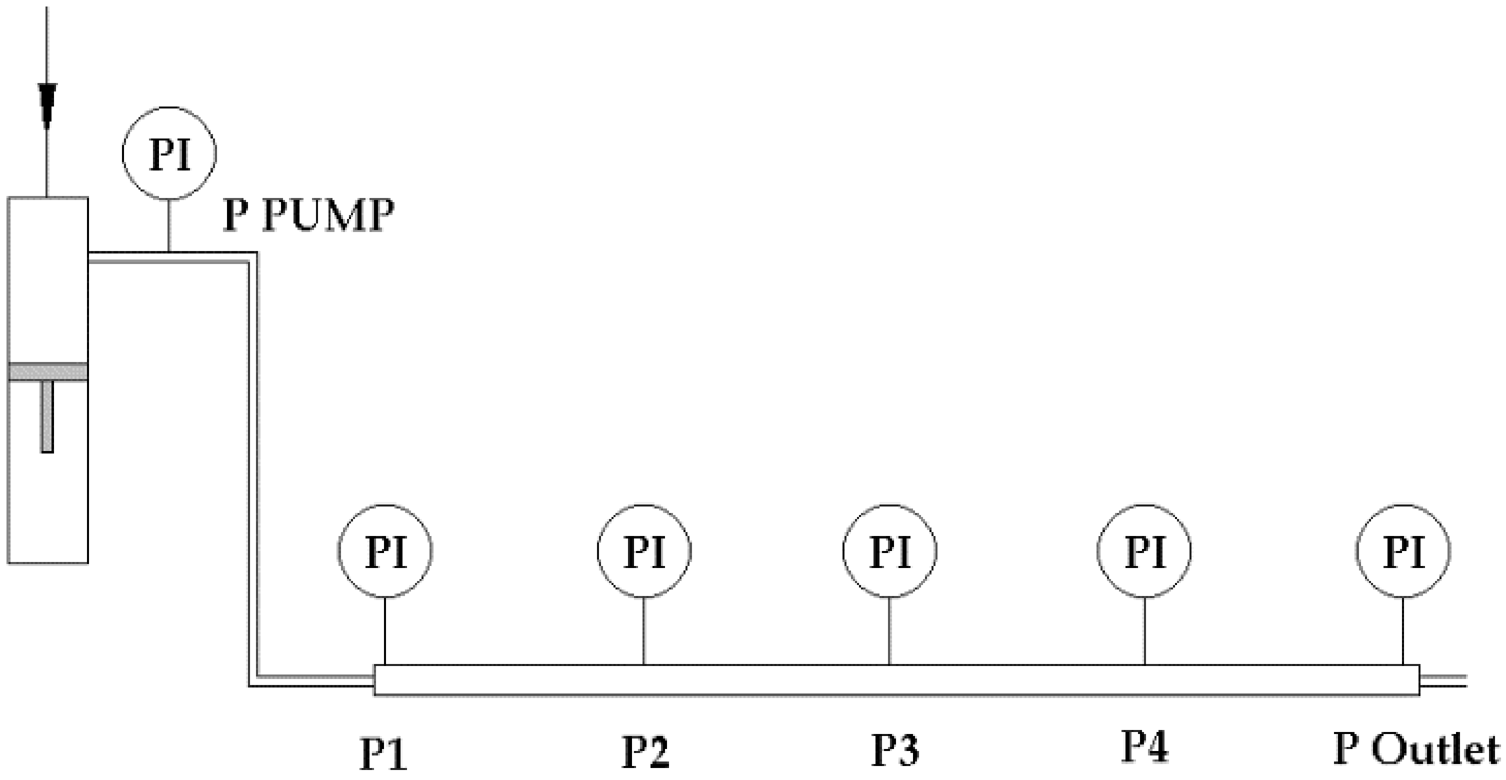
The lab – the working principle.

- Step 1: Pipes are filled with crude oil.



The lab – the working principle.

- Step 1: Pipes are filled with crude oil.
- Step 2: Temperature of piping is controlled by cooling equipment.



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- Step 1: Pipes are filled with crude oil.
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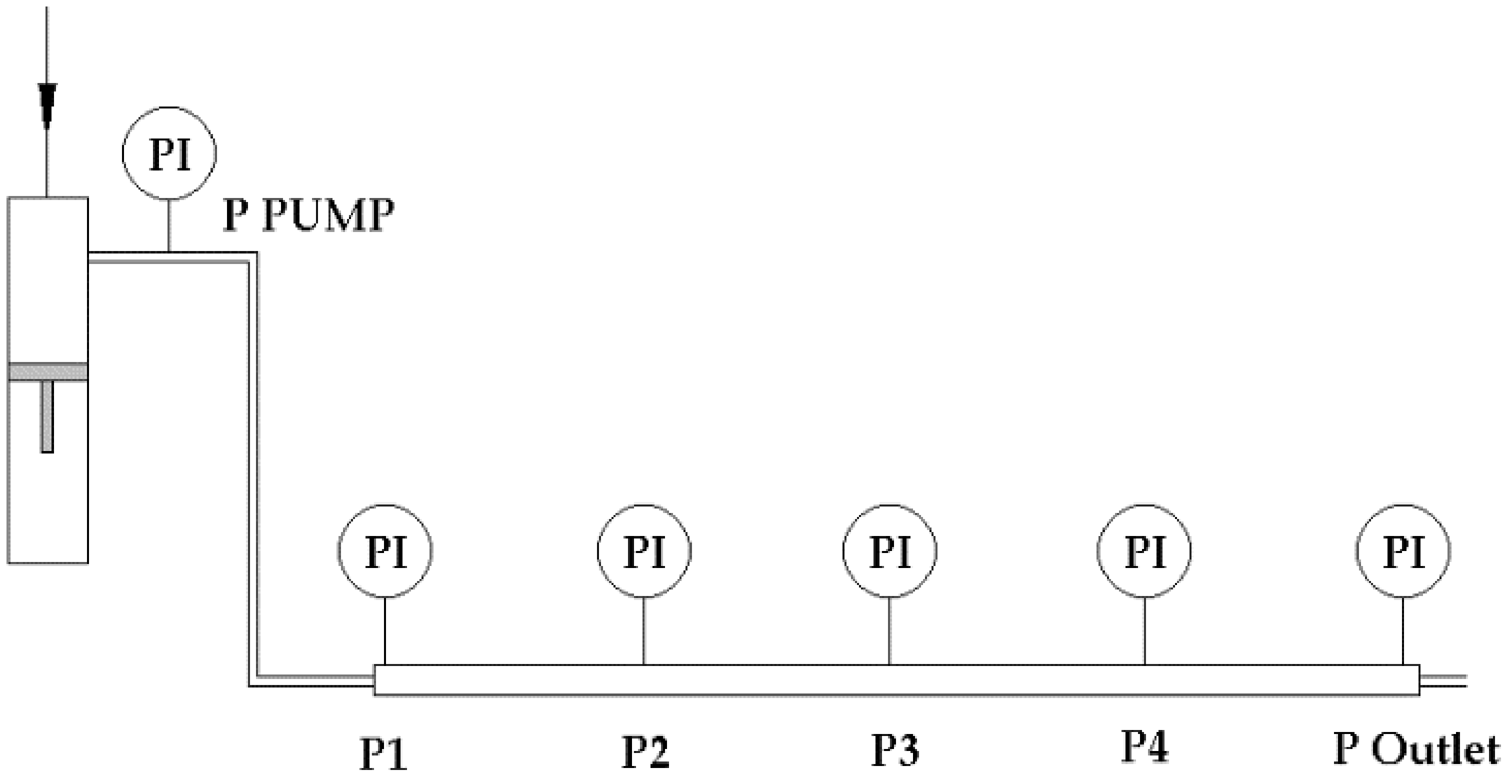
- Step 3: Pump is activated delivering fresh fluid pushing the gel towards outlet.



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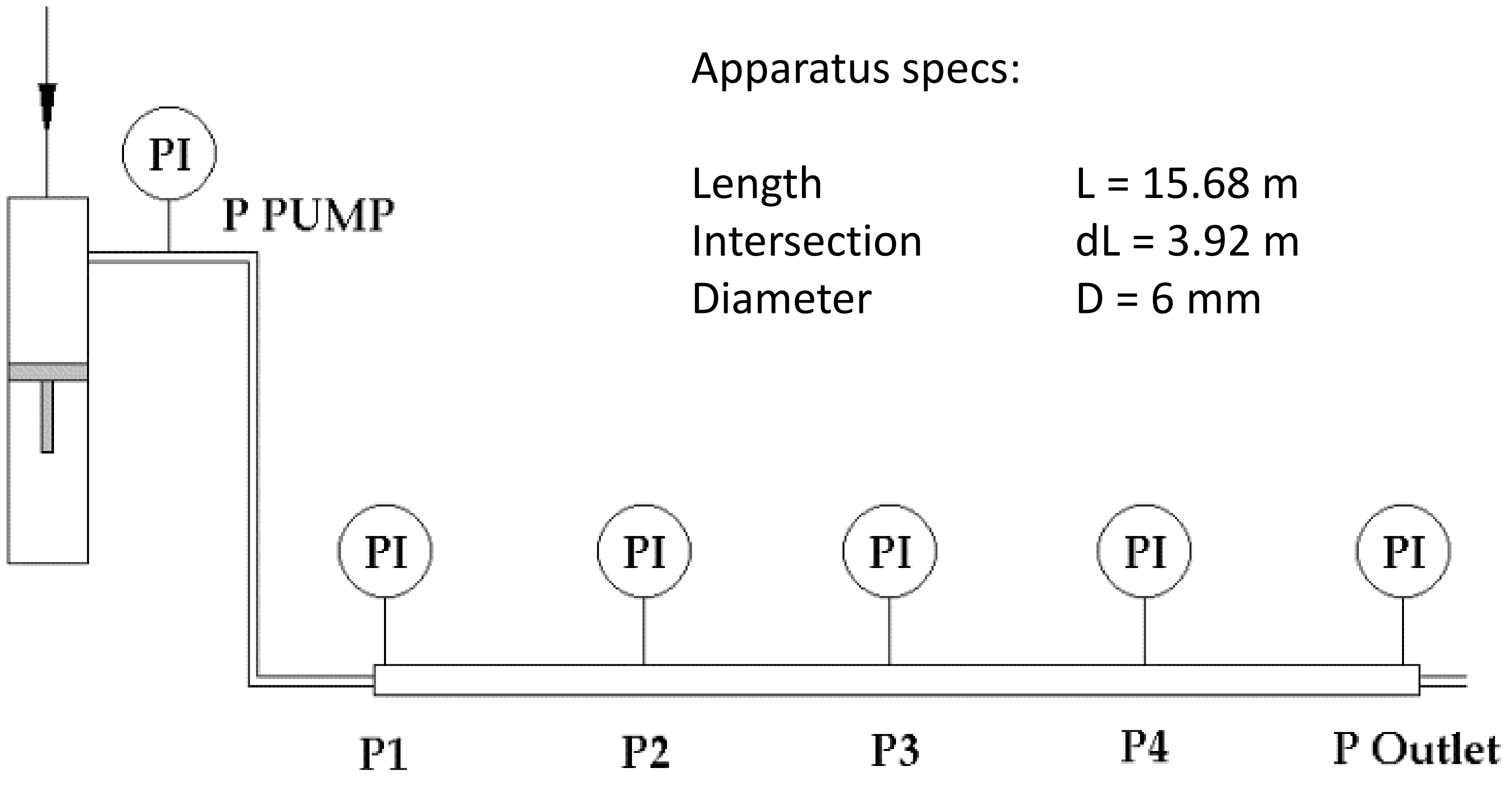
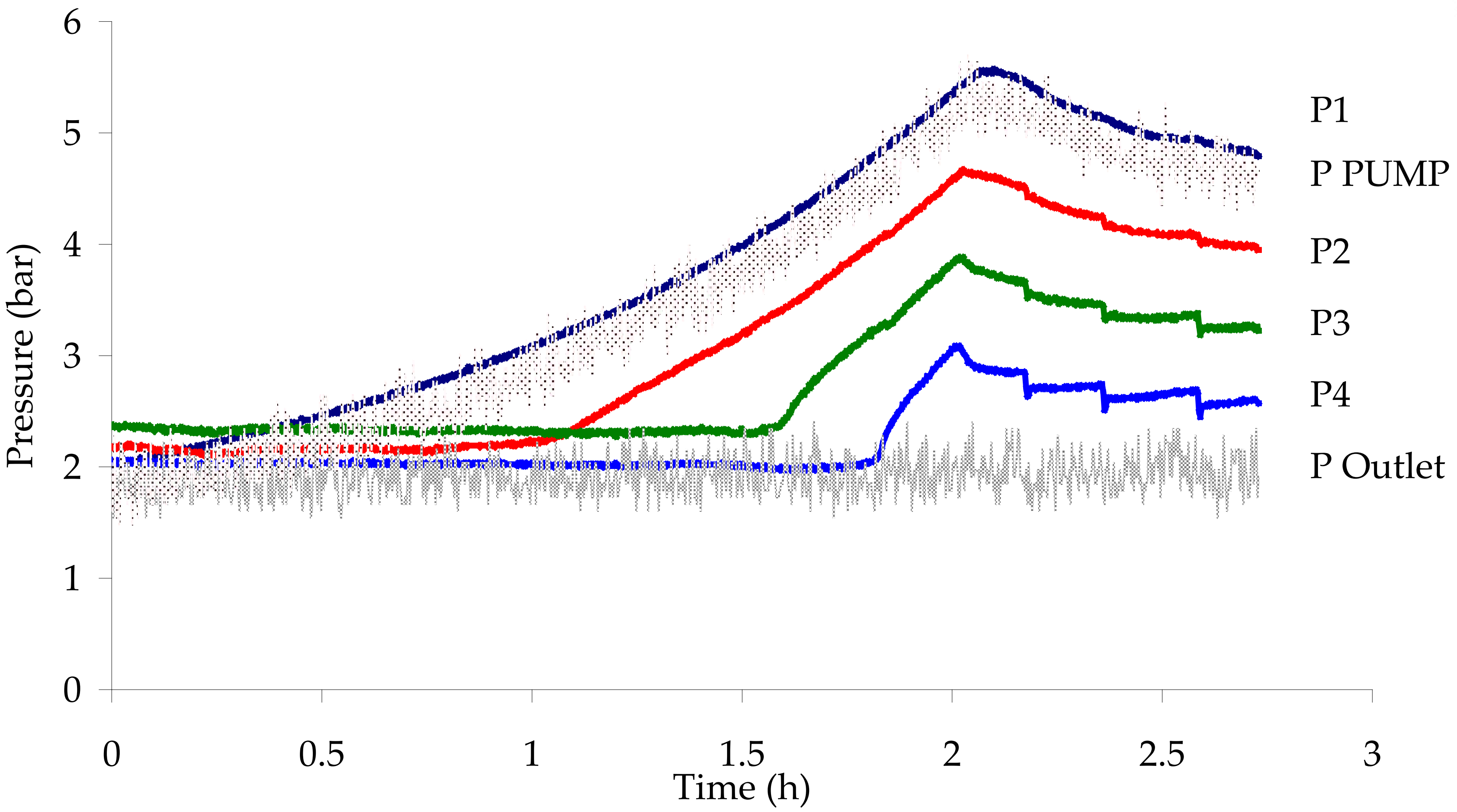


Apparatus specs:

Length	L = 15.68 m
Intersection	dL = 3.92 m
Diameter	D = 6 mm

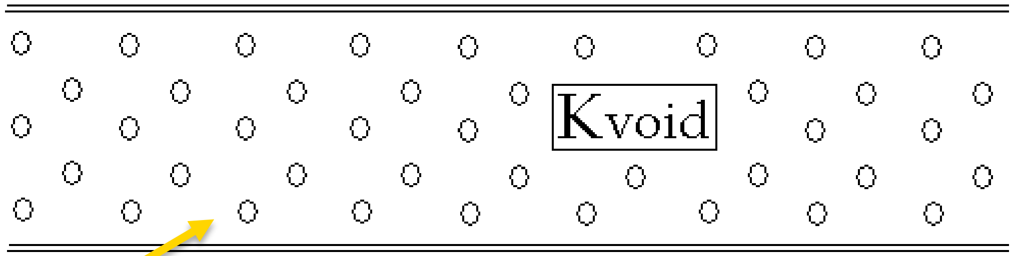
The lab – outcome.

- Pressure is monitored at 5 positions during time.
- Notice clouds of points:
  - P PUMP
  - P Outlet
- Notice blue line P4:
  - Avalances after peak
- Pressure-peak after 2h:
  - i.e. gel starts to move



The lab – multiphase conditions.

- As before, the cold waxy gel is formed.
  - Phase transition takes place.
- In case of longer time without flow:
  - Ageing of gel
  - The gel becomes more compact
  - Volume change due to solidification
  - Voids start to appear
  - Hence: Non-Newton liquid + solids + gas pockets



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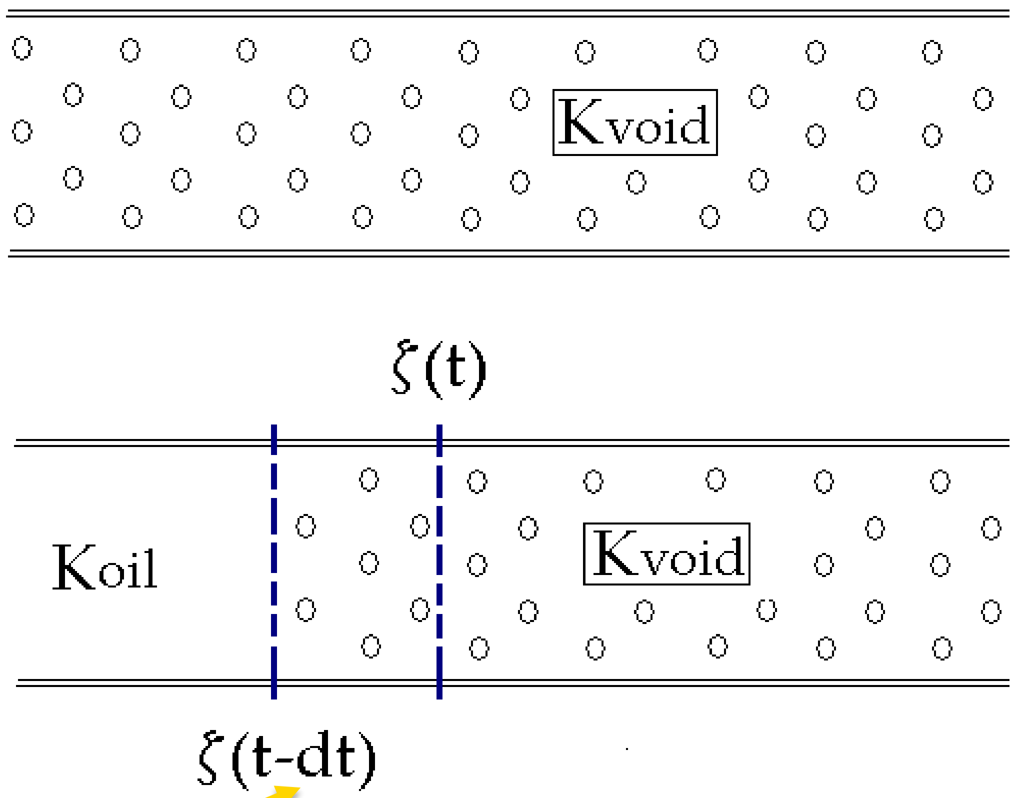
- Restart of flow:
  - Push gel mixture with oil.
  - Pressure and stress act in a interface ZONE
  - Beyond the ZONE no pressure change appears



How to model wax?

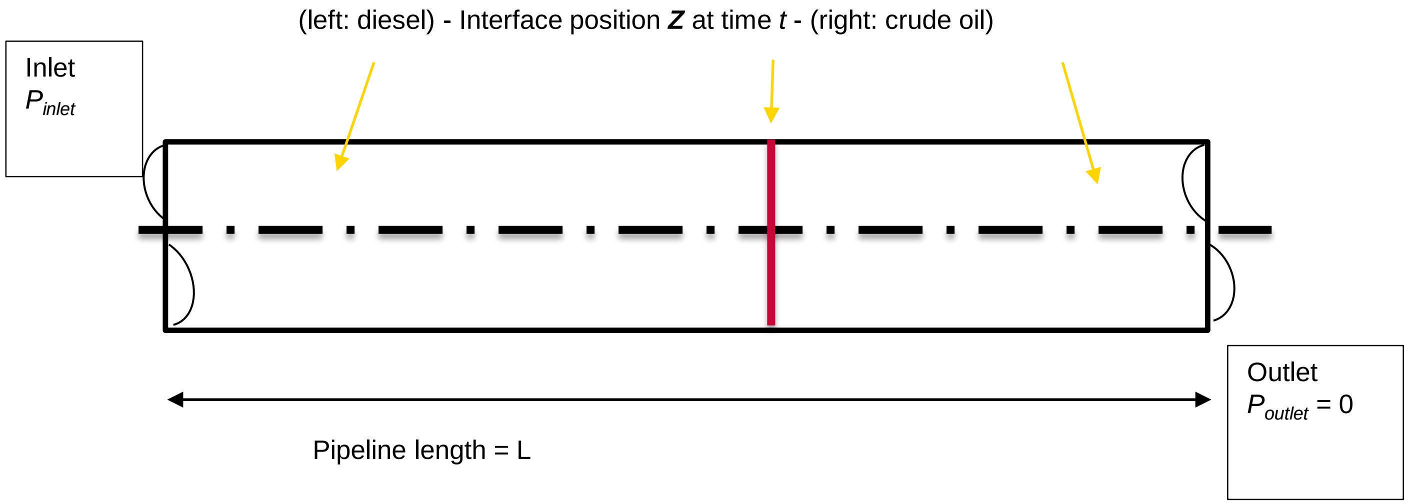
Start with a model from literature…

[Startup flow of gelled crudes in pipelines; de Souza Mendes et. Al.; Journal of Non-Newtonian Fluid Mechanics; 2012]

Modelling of pipe.

The numerical model of production-restart is limited to:

- -only the flow inside the pipeline
- -other parts of production facilities are excluded
- -e.g. valves
- -e.g. separators, etc.

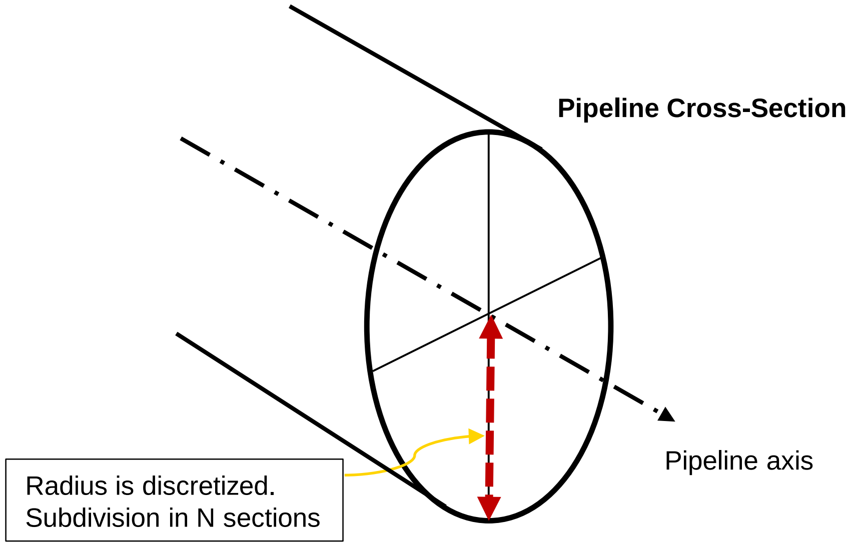


Consists of two fluid lumps.

Modelling of fluid.

As proposed in paper:

- Interface between a Newtonian and a NON-Newtonian is tracked.
- The NON-Newtonian fluid is modelled with a Thixotropic behaviour.
- Velocity profile and Structure-Function is modelled on cross-section.



A very simple model indeed.

Newtonian equations and structure function.

Position of interface between fluids 'Z':

$$\frac{dz}{dt} = \overline{U}(t)$$

Newtons law:

$$\left(\rho_{diesel} z + \rho_{crude}(L - z)\right)\frac{d\overline{U}}{dt} = P_e - \frac{2}{R}\left(\tau_{diesel}\, z + \tau_{crude}(L - z)\right)$$

The structure parameter lambda.

In general it is a function of both stress and also time.

When λ=1.0 then the fluid is with max structure, i.e. implicates largest possible viscosity (a gel).

When λ=0.0 the viscosity is at minimum.

$$\lambda = \lambda(\tau, t)$$

Equation set for thixotropic model.

Viscosity function:

$$\eta(\lambda) = \left(\frac{\eta_0}{\eta_\infty}\right)^{\lambda} \eta_\infty$$

Stress equation:

$$\tau = \eta_{eq}(\dot{\gamma}_{eq})\dot{\gamma}_{eq}$$

Viscocity function for viscoplastic materials:

$$\eta_{eq}(\dot{\gamma}_{eq}) = \left[1 - e^{\left(-\frac{\eta_0 \dot{\gamma}_{eq}}{\tau_0}\right)}\right]\left\{\frac{\tau_0}{\dot{\gamma}} + K\dot{\gamma}_{eq}^{n-1}\right\} + \eta_\infty$$

Structure function:

$$\frac{d\lambda}{dt} = \frac{1}{t_{eq}}\left[(1-\lambda)^a - \left(1 - \lambda_{eq}(\tau)\right)^a \left(\frac{\lambda}{\lambda_{eq}(\tau)}\right)^b\right]$$

Deformation rate becomes shear rate:

$$\dot{\gamma}(r,t) = -\frac{\partial v_z}{\partial r}(r,t)$$

Simple mean velocity and -profile relation:

$$\bar{U}(t) = \frac{1}{\pi R 2}\int_0^R 2\pi r v \, dr$$

Tuning the thixotropic model.

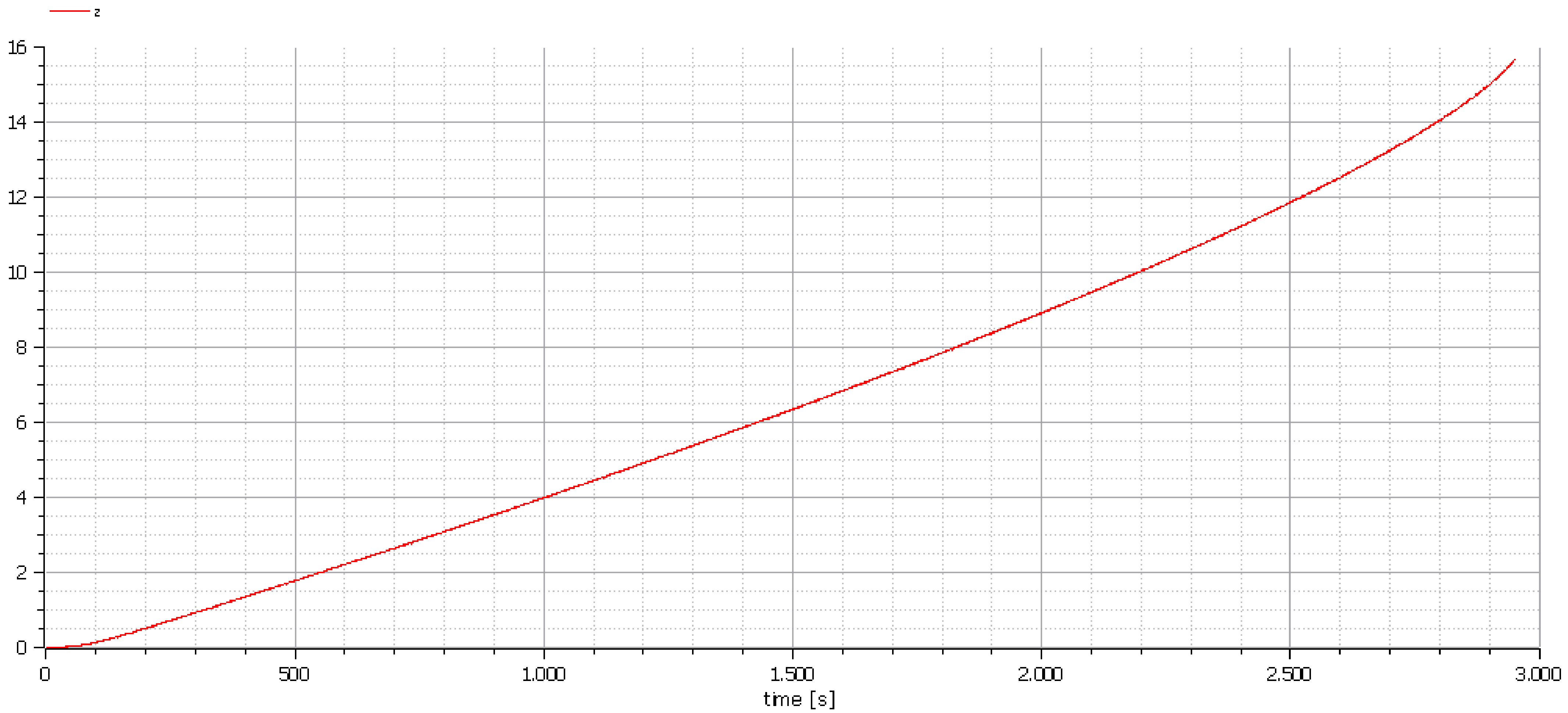
- A two step procedure.
- Of course begin with DATA set inserted and a start to iterate…
- …search for adequate numerical values of tuning parameters

DATA

Density	800 kg/m3
Yield stress	31.7 Pa
Oil visc.(newton)	0.22 Pa/s

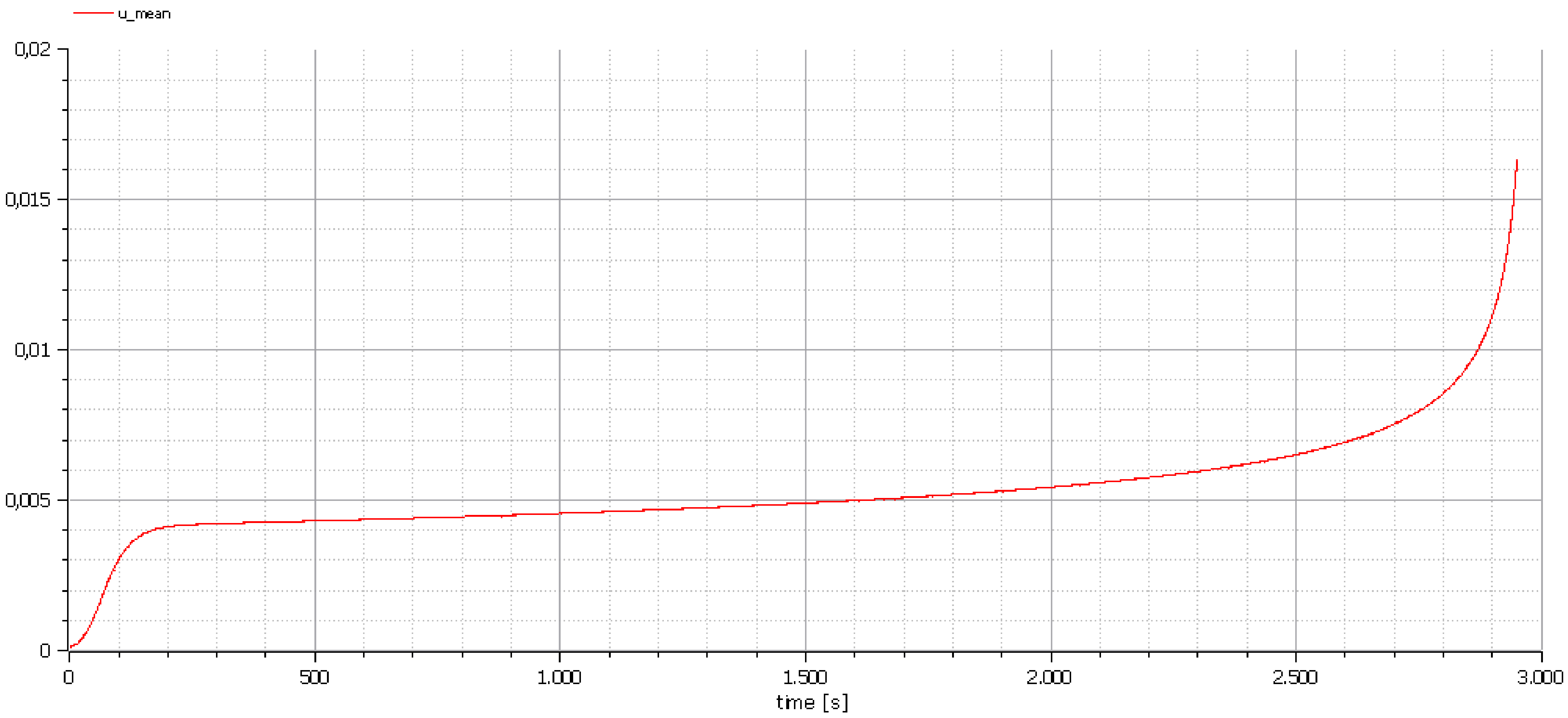
- Viscosity function values
  - Min 0.22
  - Max 31.7

Simulations – interface tracking.



Notice the time: Completely different from experimental observation.

Simulations – interface speed.



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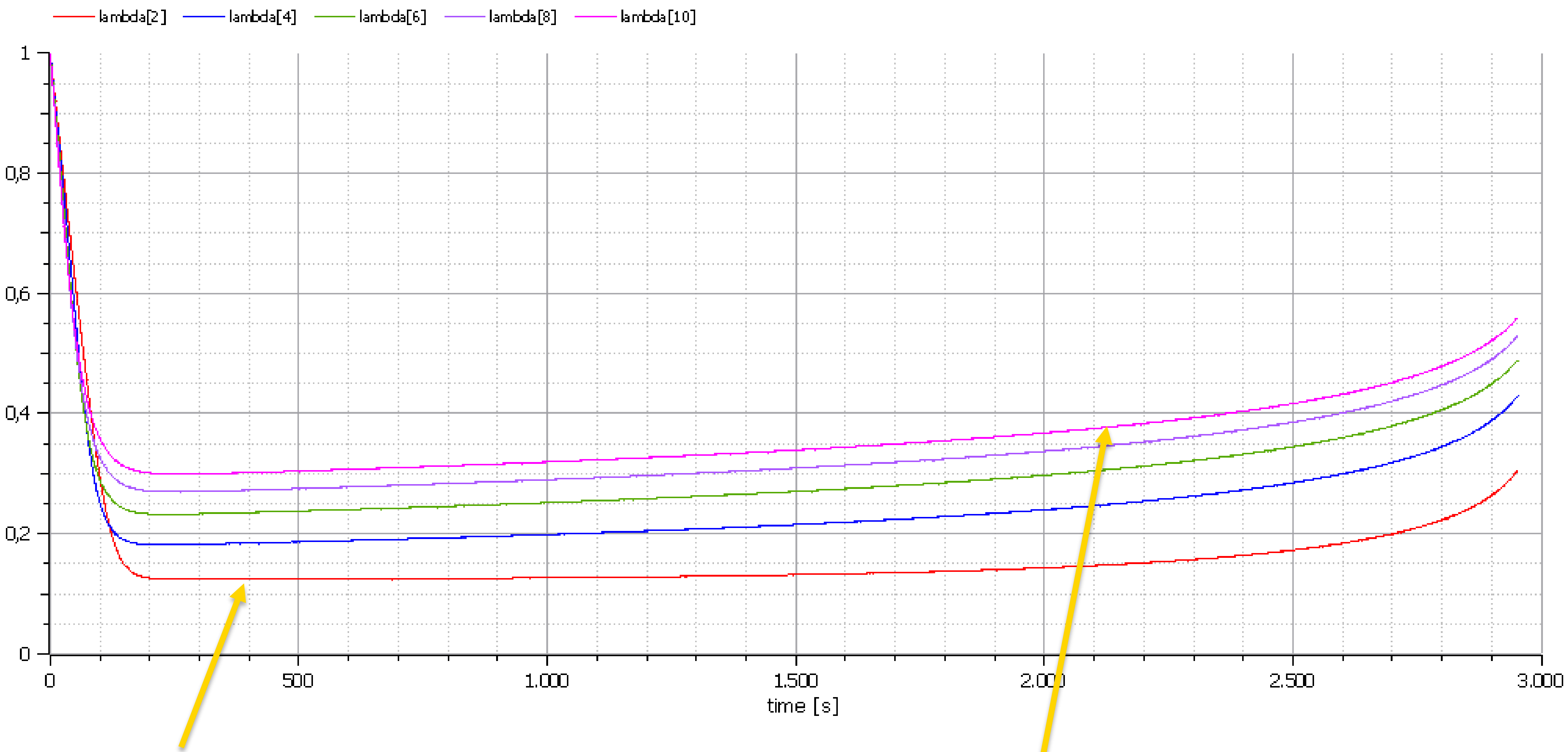
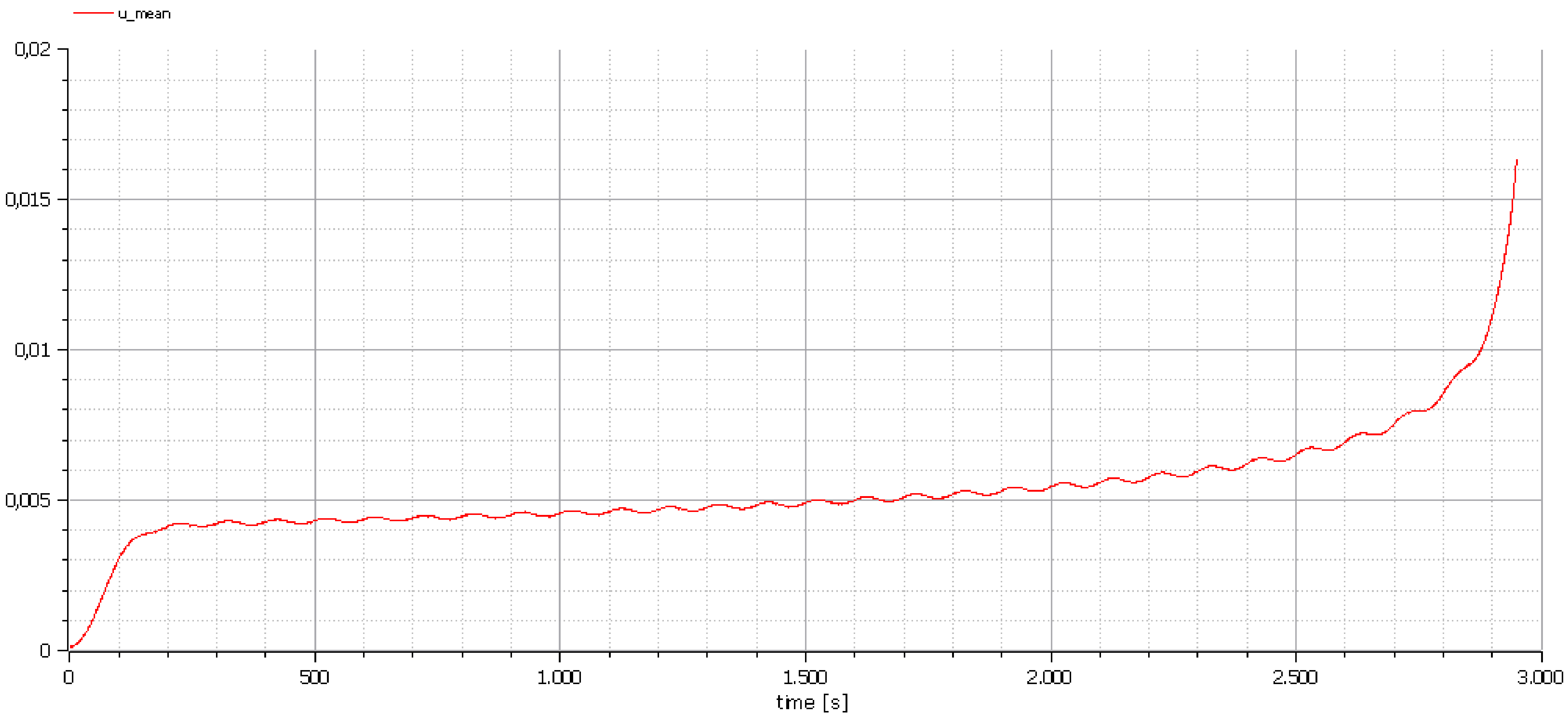
Simulations – interface tracking.



Lambda[2] is close to pipe axis.

Lambda[10] is close to pipe wall.

Recall Pressure cloud: Simulations – interface speed with inlet pressure oscillations.



Frequency: 0.01 Hz; sinusoidal; amplitude 0.01 bar

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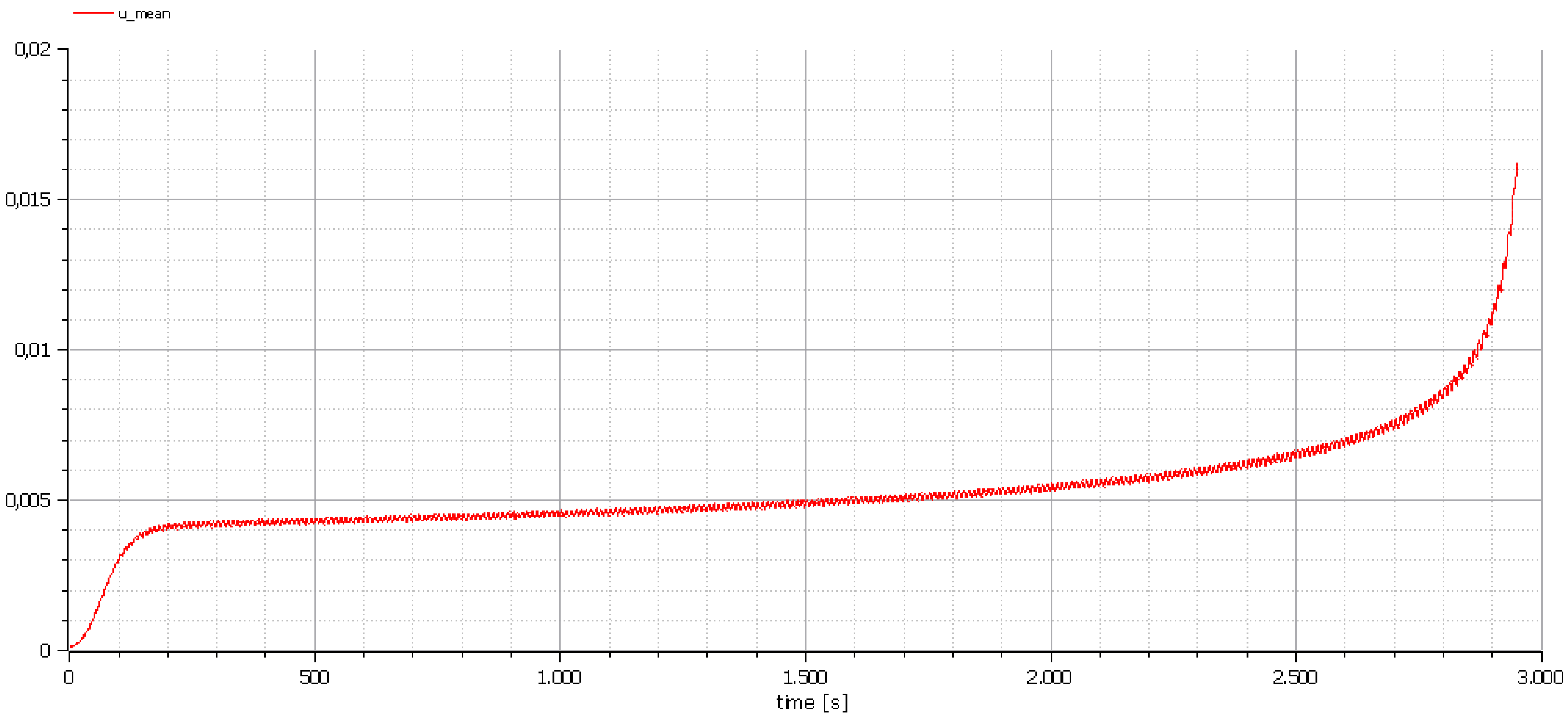
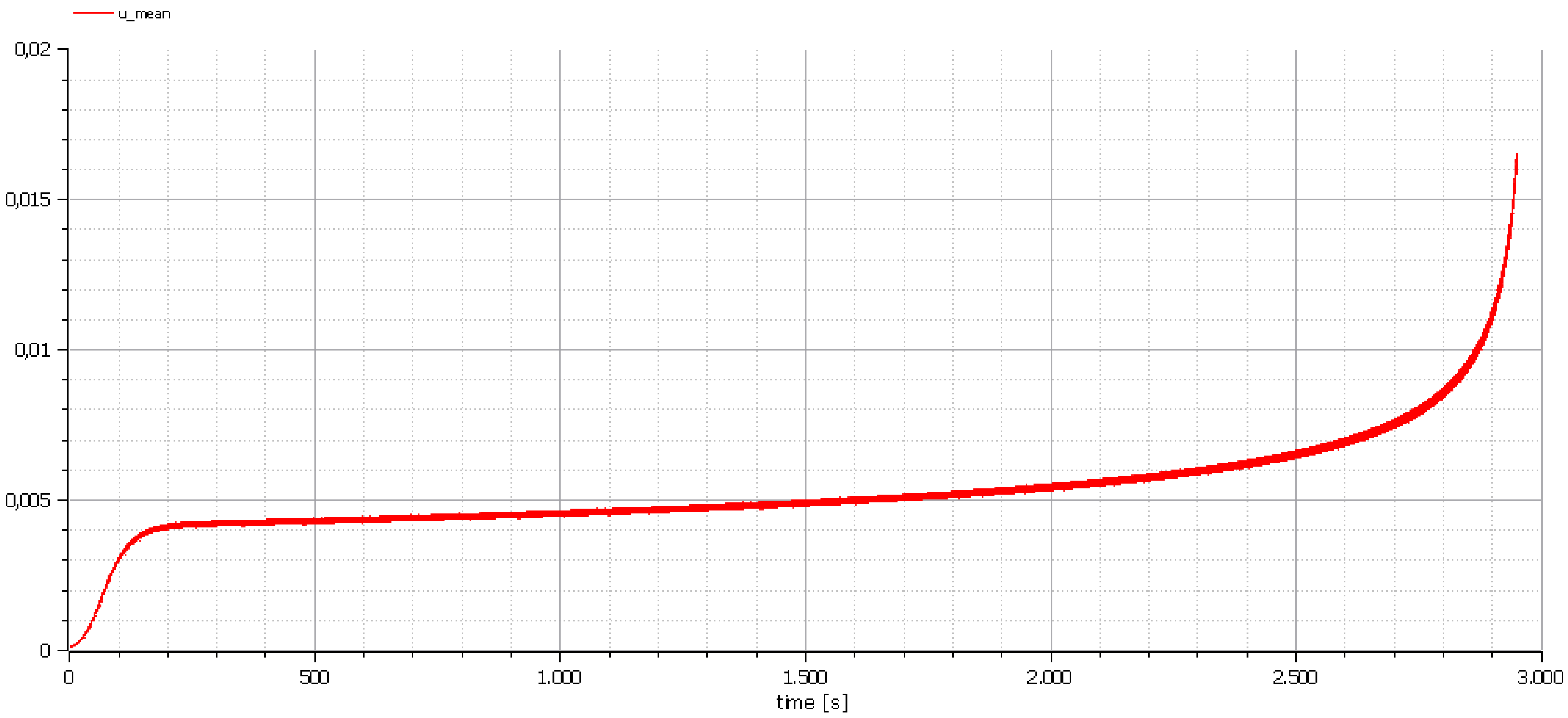


Frequency: 0.10 Hz; sinusoidal; amplitude 0.01 bar

Recall Pressure cloud: Simulations – interface speed with inlet pressure oscillations.



Frequency: 1.00 Hz; sinusoidal; amplitude 0.01 bar

Conclusion.

- Simple thixotropic model from literature has been implemented (in Modelica).
- Experimental outcomes have been analyzed for restart of gelled crude.

- Tuning of the thixotropic model has been performed, however:
  - Time-scale of restart is beyond a factor two!
  - Structure function (Lambda) increases towards end of simulation! It should be a memory function, i.e. the longer time the fluid has been stirred then the structure function decrease

Tweaking numerical model-parameters is not sufficient to capture significant physics.

- Modelica has been deployed for model development.
  - A fast tool for ODE/DAE systems development.
  - However, needs special attention of “start-up” conditions
  - (Although not reported here, PDE’s are a completely different story – maybe next time…)