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

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by Keld Lund Nielsen & Sebastiano Correra
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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)
What happens in the pipeline transporting waxy crudes?

- Crude oil flows into the pipeline, temperature is high.

\[ T > WAT \]
\[ Q = Q_o \]

No Deposit
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.

\[
\begin{align*}
T > \text{WAT} & \quad Q = Q_0 \\
\text{WAT} > T > \text{PP} & \quad Q = Q_0
\end{align*}
\]

- No Deposit
- Small Deposit
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.
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- 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.

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The lab – the working principle.

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- **Step 2**: Temperature of piping is controlled by cooling equipment.

- **Step 3**: Pump is activated delivering fresh fluid pushing the gel towards outlet.

**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’:

\[ \frac{dz}{dt} = \bar{U}(t) \]

\[ (\rho_{\text{diesel}} z + \rho_{\text{crude}} (L - z)) \frac{d\bar{U}}{dt} = P_e - \frac{2}{R} (\tau_{\text{diesel}} z + \tau_{\text{crude}} (L - z)) \]

\[ \lambda = \lambda(\tau, t) \]

Newtons law:

The structure parameter lambda.

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

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

When \( \lambda = 0.0 \) the viscosity is at minimum.
Equation set for thixotropic model.

Viscosity function:
\[ \eta(\lambda) = \left( \frac{\eta_0}{\eta_\infty} \right)^{\lambda} \eta_\infty \]

Stress equation:
\[ \tau = \eta_{eq}(\dot{\gamma}_{eq}) \dot{\gamma}_{eq} \]

Viscosity function for viscoplastic materials:
\[ \eta_{eq}(\dot{\gamma}_{eq}) = \left[ 1 - e^{-\frac{\eta_0\dot{\gamma}_{eq}}{\tau_0}} \right] \left\{ \frac{\tau_0}{\dot{\gamma}} + K \dot{\gamma}^{n-1} \right\} + \eta_\infty \]

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

Deformation rate becomes shear rate:
\[ \dot{\gamma}(r, t) = -\frac{\partial v_z}{\partial r}(r, t) \]

Simple mean velocity and -profile relation:
\[ \bar{U}(t) = \frac{1}{\pi R^2} \int_0^R 2\pi r v(r, t) dr \]
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
Notice the time: Completely different from experimental observation.
Simulations – interface speed.

Notice the time: Completely different from experimental observation.
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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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...)