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Motivation

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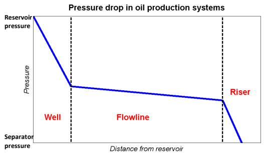
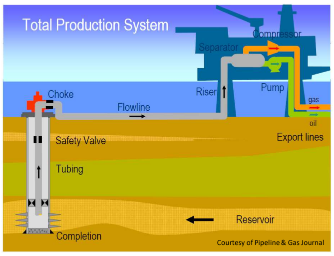
Why do we need to model multiphase flow in vertical pipes?

Oil production:

Majority of pressure is lost in wells and risers:
<u>Must predict the pressure drop here accurately to predict production rate.</u>





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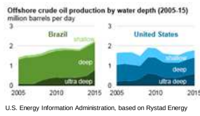
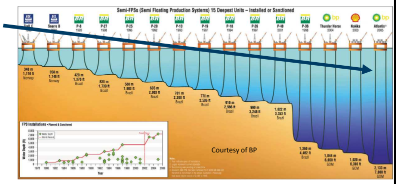
Why do we need to model multiphase flow in vertical pipes?

Deep water risers:

- **New oil discoveries are found at increasing depths.**
- **Example: Atlantis field in GOM: <u>2,133 m</u>.**
- **In this case, a <u>10% (0.1) error</u> in the liquid holdup prediction would yield an error of <u>17 bar</u> in the total pressure drop.**
- **=> Deep water developments need accurate models to minimize uncertainties in design and economic feasibility.**

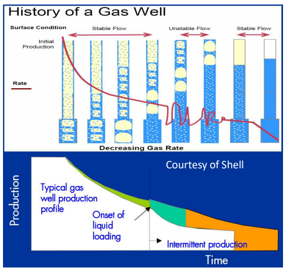




Why do we need to model multiphase flow in vertical pipes?

Gas production:

- **Liquid accumulation at low rates (late life) => wells die if untreated.**
- **Important question: <u>When does the liquid start to accumulate?</u>**
- **If we know that, we can assess:**
  - **Economic feasibility**
  - **When to start remedial procedures (e.g. boosting)**
  - **Gas lift allocation (how much gas is needed)**



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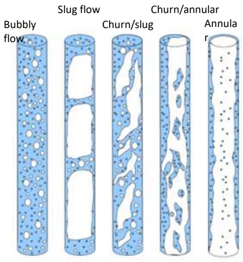
Modelling of vertical flow

How can we model multiphase flow in vertical pipes?

1D modelling:

- **Need assumptions regarding the phase distribution – "flow regimes"**
- **Need also closure laws for:**
  - **Interfacial and wall shear stresses**
  - **Bubble/droplet entrainment**
  - **Bubble rise velocities**

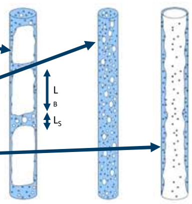


How can we model multiphase flow in vertical pipes?

***Unit Cell Model*: The flow is a train of liquid slugs and large bubbles (slug flow), with slug fraction SF = $L_S/(L_S + L_B)$.**

Special case 1: SF=1 => Bubbly flow (no large bubbles)

Special case 2: SF=0 => Annular flow (no slugs)

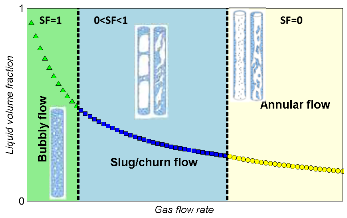


How can we model multiphase flow in vertical pipes?

Conservation of mass and momentum + some necessary closure models.

Solving the equations yield:
- Pressure drop
- Phase fractions
- Slug fraction SF

Flow regimes are predicted from continuity.



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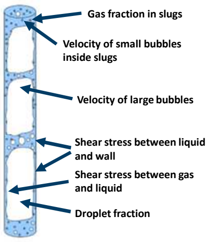
What closure laws do we need?



With these closure laws, combined with mass- and momentum conservation equations, we can calculate the phase fractions, pressure drop and flow regime for a given set of flow conditions (pipe diameter, pipe angle, flow rates and thermodynamic properties).

We have derived expressions for these closure laws using experimental data.

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Recent efforts on deriving new closure laws

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New experimental campaign on vertical flow

Aim:
Produce data suitable for deriving more accurate closure laws for vertical flows.

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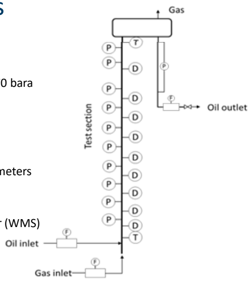
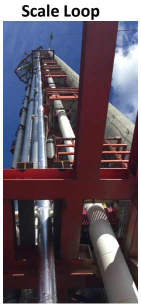
New experiments

- D=4", L = 51 m
- Gas: Nitrogen @ 20, 45 and 70 bara (23-80 kg/m^3)
- Liquid: Exxsol D60
- Instruments:
  - 10 DP-cells
  - 9 static gamma densitometers
  - 1 traversing gamma densitometer
  - 1 dual wire mesh sensor (WMS)



SINTEF Large Scale Loop



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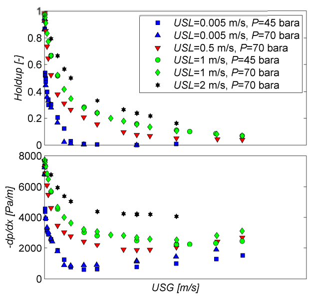
Sample results

Time-averaged liquid fraction and pressure drop.



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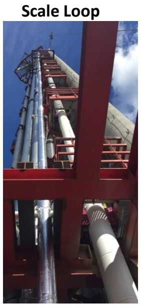

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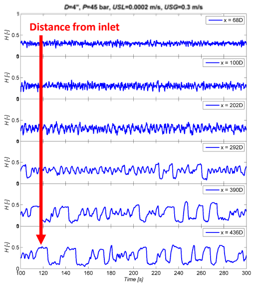
Why such a long pipe?

Slug/churn flow:

A long pipe is needed to obtain steady-state flow characteristics.



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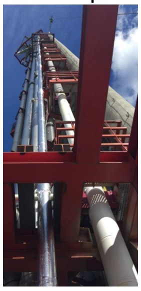

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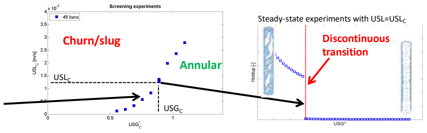
Experiments part 1: Gas dominated flows

For very low liquid rates (like in gas wells), there can be a discontinuous transition from annular flow to churn/slug flow.

This transition is mainly controlled by the interfacial shear stress.

We conducted special experiments to map out this discontinuous transition.



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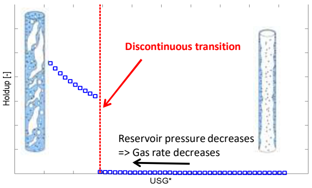
Experiments part 1: Gas dominated flows

Predicting this discontinuous transition is critical for gas wells:

When the gas rate falls below the critical value, the well starts to fill up with liquid, significantly decreasing production ("liquid loading").

=> Intervention needed to sustain production.



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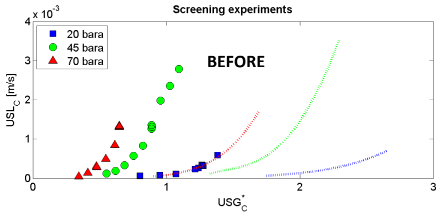
Gas dominated flows

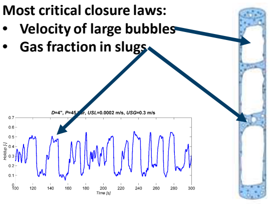
New model for interfacial shear stress developed based on the new data.

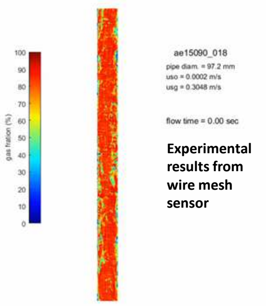


The lines represent predictions with LedaFlow 2.0 (old model)

Experiments part 2: Liquid dominated flows

Most critical closure laws:
- Velocity of large bubbles
- Gas fraction in slugs





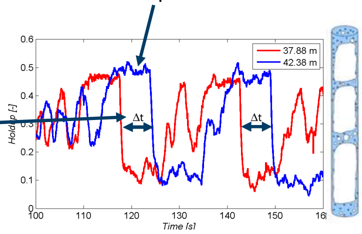
Experimental results from wire mesh sensor

Experiments part 2: Large bubble velocity

Gas fraction in slugs obtained from semi-automatic analysis of holdup time traces.

Velocity of large bubbles measured by cross-correlating liquid holdup time traces:

$$U_B = \frac{\Delta x}{\Delta t}$$



Modelling the large bubble velocity

$$u_B = C_0 u_M + U_0$$

Derived from the velocity profile in the slugs

$$C_0 = \frac{(n+1)(2n+1)}{2n^2}\left[1 - \frac{2}{Eo}\left(3 - \log_{10}(\mathrm{Re}_m)\,\mathrm{e}^{-0.025Eo}\right)\right] \qquad n = \kappa\sqrt{\frac{2}{f}}$$

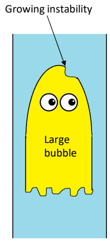
$$\frac{U_0}{\sqrt{g'D}} = -\frac{8}{3}\frac{\nu(1+8s)}{\sqrt{g'D^3}} + \frac{\sqrt{2}}{3}\left[1 - 2s - \frac{16s\sigma}{\rho g' D^2} + \frac{32\nu^2}{g'D^3}(1+8s)^2\right]^{\frac{1}{2}}$$

s = bubble nose curvature

$$s = s\left(\frac{t_{lifetime}}{t_{growth}},\dots\right)$$

$t_{growth} : \sqrt{\frac{\rho_l + \rho_g}{k \cdot \Delta\rho g}}$ Instability growth time scale

$t_{lifetime} : \frac{D}{u_B - u_M}$ Instability lifetime (before swept to the bubble rim)



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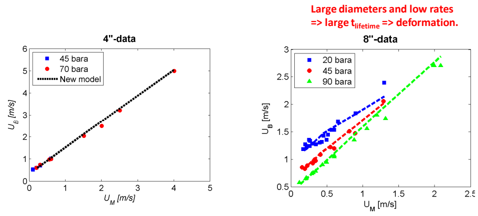
Modelling the large bubble velocity



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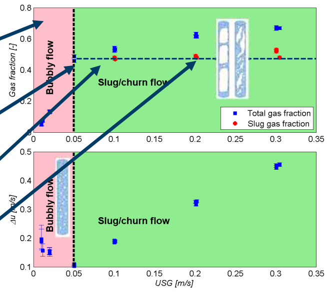
Experiments part 2: Gas fraction in slugs

USG<0.05 m/s: Bubbly flow (only small bubbles).

USG=0.05 m/s: Liquid "saturated" with small bubbles.

USG>0.05 m/s: Coalescence into larger bubbles (slug/churn flow).

Low rates: <u>The slug gas fraction equals the gas fraction at the transition.</u>



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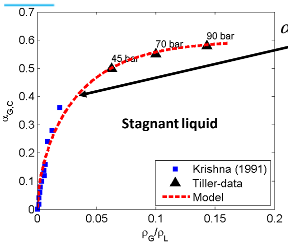
Experiments part 2: Gas fraction in slugs



$$\alpha_G^{slug} = \alpha_{G,C} + G\left(Ku_{slug}, \mathrm{Re}_{slug}\right)$$

Gas fraction at the bubbly/slug transition

In slug/churn flow, turbulent mixing at the bubble wake can increase the bubble saturation

$$Ku_{slug} = \frac{u_B - u_M}{\left(\frac{\sigma g \Delta\rho}{\rho_l^2}\right)^{\frac{1}{4}}}$$

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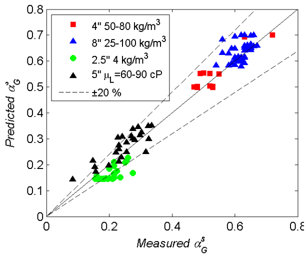
Experiments part 2: Gas fraction in slugs

Validated for several diameters (2.5"-8"), gas densities (4-100 kg/m³) and liquid viscosities (1-90 cP).



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Validation

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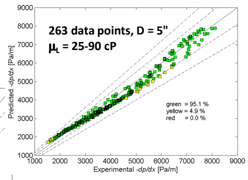
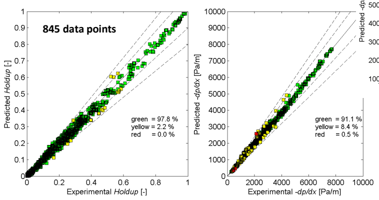
Validation: models implemented in LedaFlow





Green: dp/dx-error<10%
holdup-error<0.05

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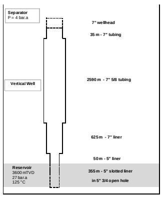
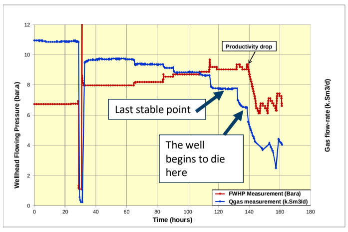
Validation: Turndown of gas well

Reducing flow by throttling the wellhead valve:
When does the well "die"?





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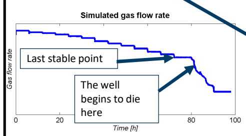
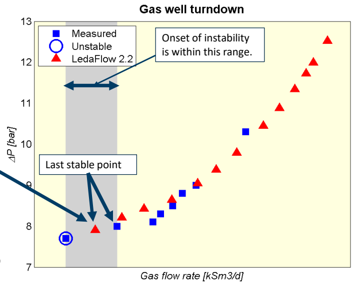
Validation: Turndown of gas well

The turndown was simulated with LedaFlow 2.2.

The predicted onset of instability is in agreement with the field measurements.





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Conclusions

- Accurate models for multiphase flows in vertical pipes are needed for the design and operation of hydrocarbon production systems.
- New specially designed experiments with detailed measurements have led to significant progress in this area.
- New closure laws have been developed based on the new data, and implemented in the commerical simulation tool LedaFlow. The prevailing predictions are very accurate.

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Acknowledgements

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Questions

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Abstract

- Accurate models for multiphase flows in vertical pipes are needed for the design and operation of hydrocarbon production systems. Examples of important application areas are:
  - Predicting the time-of-death of gas wells.
  - Predicting the correct flow rate in liquid-dominated production systems, especially for deep water risers.
- In this presentation we show how vertical multiphase flow can be modelled using a 1D approach. Specifically, we explain what kind of assumptions are needed, and which physical mechanisms require closure laws. Furthermore, we show some recent experimental work conducted at industrial conditions, aimed at deriving more accurate models, and we provide some examples of how the certain closure laws have been deduced from this new data. Finally, we assemble the new closures into a unified model, and compare the predicted pressure drop and liquid content with measured values for a large experimental database on vertical flow. We also test the new model against measurements made in a 3600 meters deep gas well, where we are able to match the measured onset of liquid loading.
- The aim of the presentation is to show that vertical multiphase flow, which is known to have some very complex features, can be modelled well with 1D methods, using relatively simple assumptions.

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