Frictional pressure drop for two-phase flow of carbon dioxide in a tube: Comparison between models and experimental data

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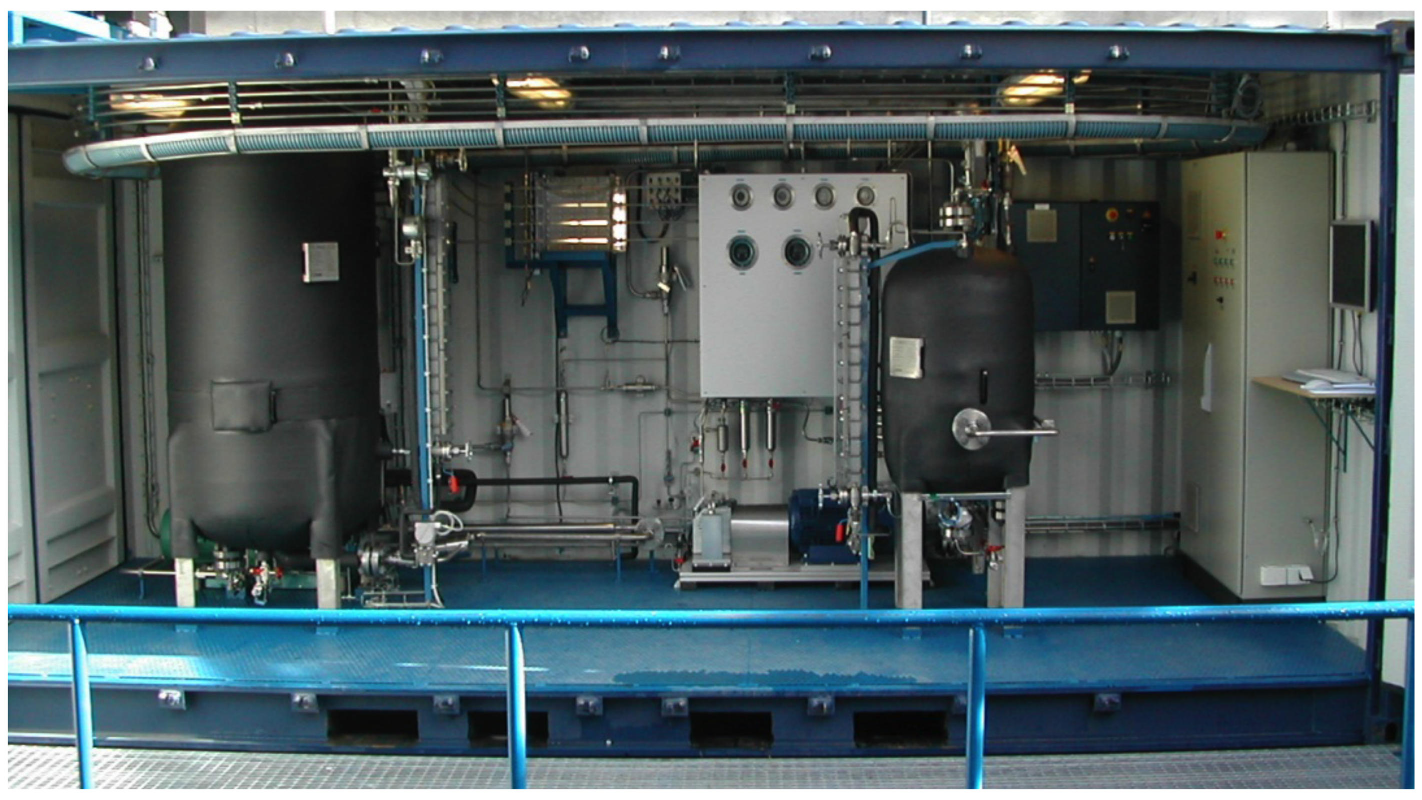
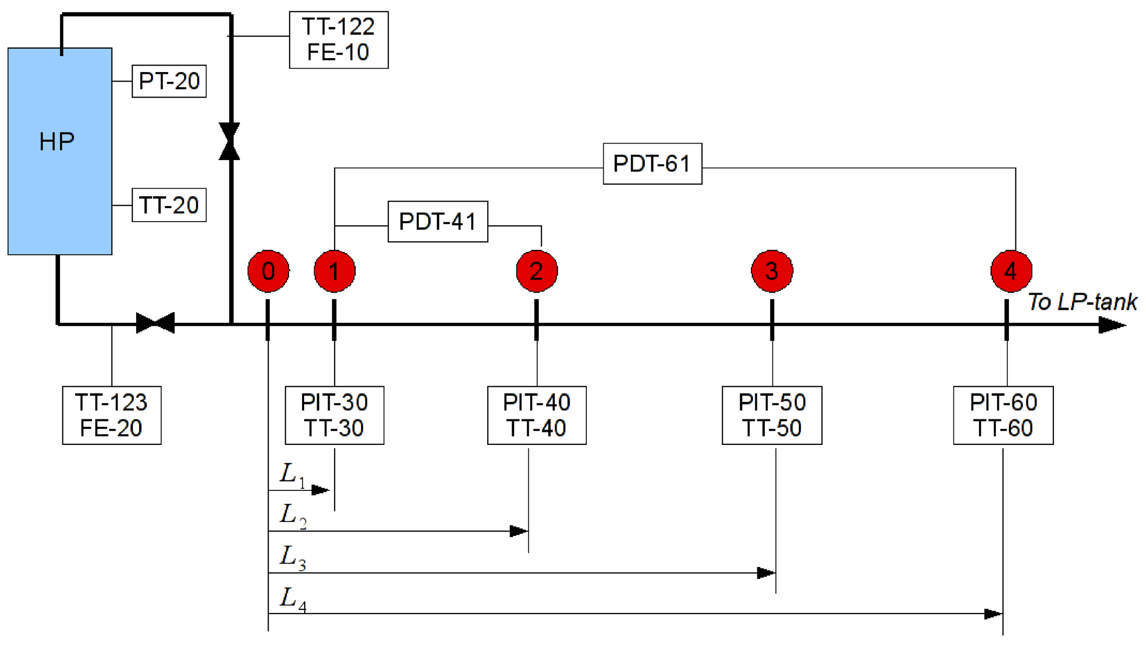
Motivation

- In CO_2 transport by pipeline, two-phase flow can occur in several situations:
  - Start-up
  - Pressure release
  - Due to intermittent supply of CO_2
  - In normal operation
- To calculate the flow in such situations, simulators need models for the frictional pressure drop (among other things)
- We therefore compare some models for frictional pressure drop with steady-state experimental data (six experiments) for pure CO_2 in tube of 10 mm inner diameter



The test rig located at the Statoil Research Centre at Rotvoll (Trondheim). Photo: Statoil.



Sensors measuring absolute pressure (PIT and PT), differential pressure (PDT), temperature (TT) and mass flow rates (FE) are placed as shown. $L_1 = 0.2\,\mathrm{m}$, $L_2 = 50.5\,\mathrm{m}$, $L_3 = 101\,\mathrm{m}$ and $L_4 = 139\,\mathrm{m}$.

Experimental conditions

Variable	Range
Mass flux, $G = \dot{m}/A$ ($\mathrm{kg/(m^2\,s)}$)	1058–1663
Flowing vapor fraction, $x = \dot{m}_\mathrm{g}/\dot{m}_\mathrm{tot}$ (–)	0.099–0.742
Saturation temperature, T (℃)	3.8–17
Reduced pressure, p_r (–)	0.52–0.72
Heat flux, q'' ($\mathrm{W/m^2}$)	−91–150.8

Sensor uncertainties

Source	Uncertainty
Temperature sensor, T	$\pm 0.5\,\mathrm{K}$
Absolute-pressure sensor, p	$\pm 0.16\,\mathrm{bar}$
Differential-pressure sensor, Δp	$\pm 0.05\,\mathrm{bar}$
Gas-flow meter, $\dot{m}_G$	$\pm 0.06\,\%$
Liquid-flow meter, $\dot{m}_L$	$\pm 0.3\,\%$

The models

- In the *Friedel model*, the wall-friction force is calculated as

$$F_\mathrm{w} = \frac{1}{2}\frac{f_{\ell o}|G|G}{\rho_\ell d_\mathrm{h}}\Phi.$$

  Φ is a two-phase frictional multiplicator – an empirical correlation

$$\Phi = \Phi(Fr, We, f_{\mathrm{g}o}, f_{\ell o}, \rho_\mathrm{h}, \rho_\mathrm{g}, \rho_\ell, \mu_\mathrm{g}, \mu_\ell, x).$$

- The *Cheng et al.* model was developed specifially for CO_2 and includes phenomenological models for various flow patterns.
- The *homogeneous flow* is the simplest kind of model, where the quantities are calculated assuming no slip between the phases.

Friction-model error for all the experiments

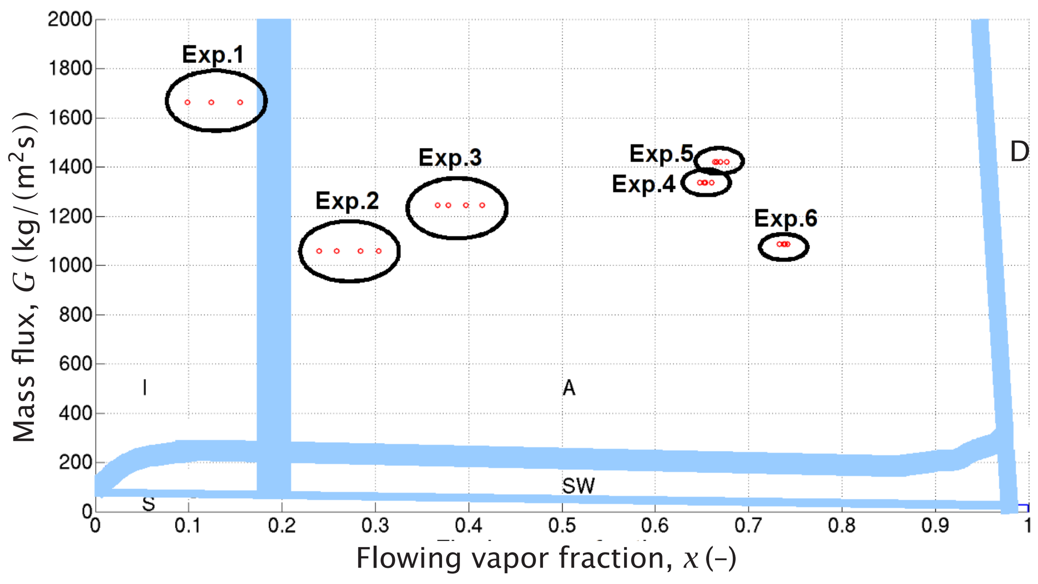
Model	s_R (%)	$\bar{e}$ (%)
Friedel	9.7	8.13
Cheng *et al.*	57.74	19.93
Homogenous	29.18	19.11

… and for high flowing vapor fraction

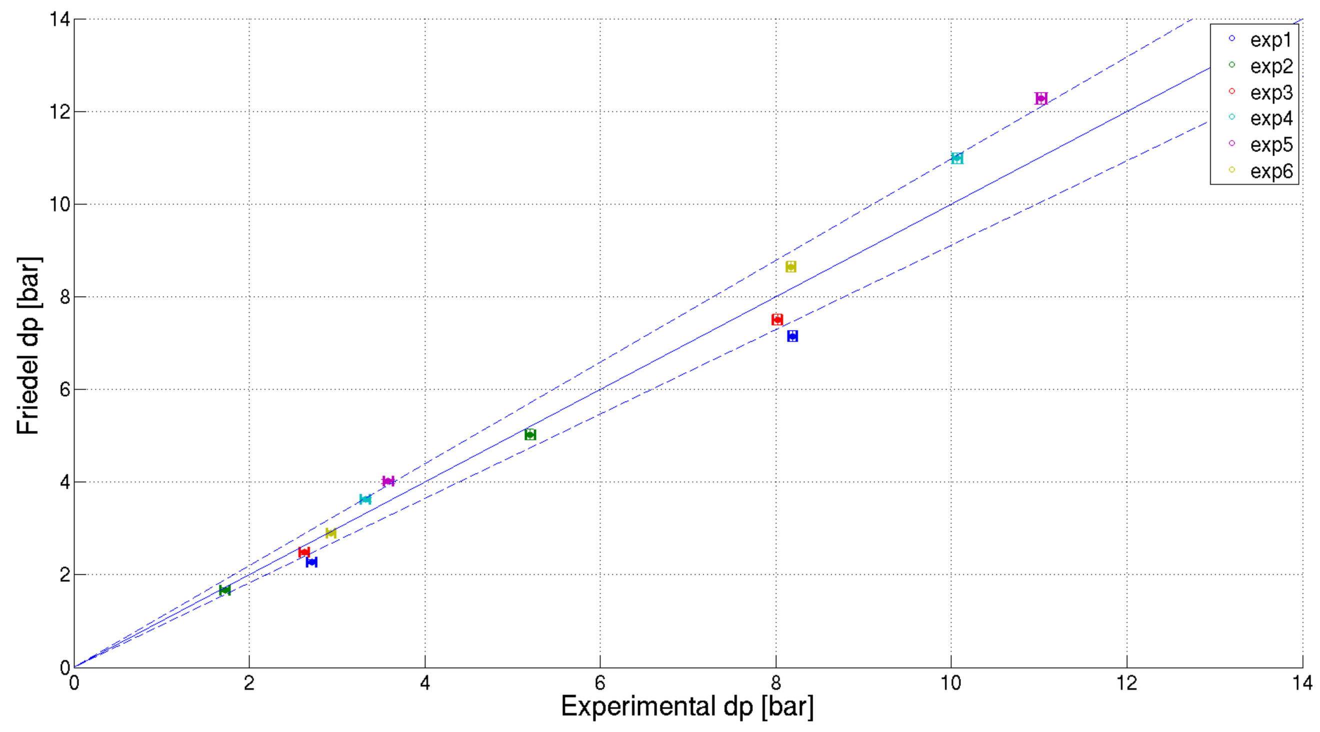
Model	s_R (%)	$\bar{e}$ (%)
Friedel	10.2	8.78
Cheng *et al.*	1.85	1.35
Homogenous	20.12	12.92

Conclusions

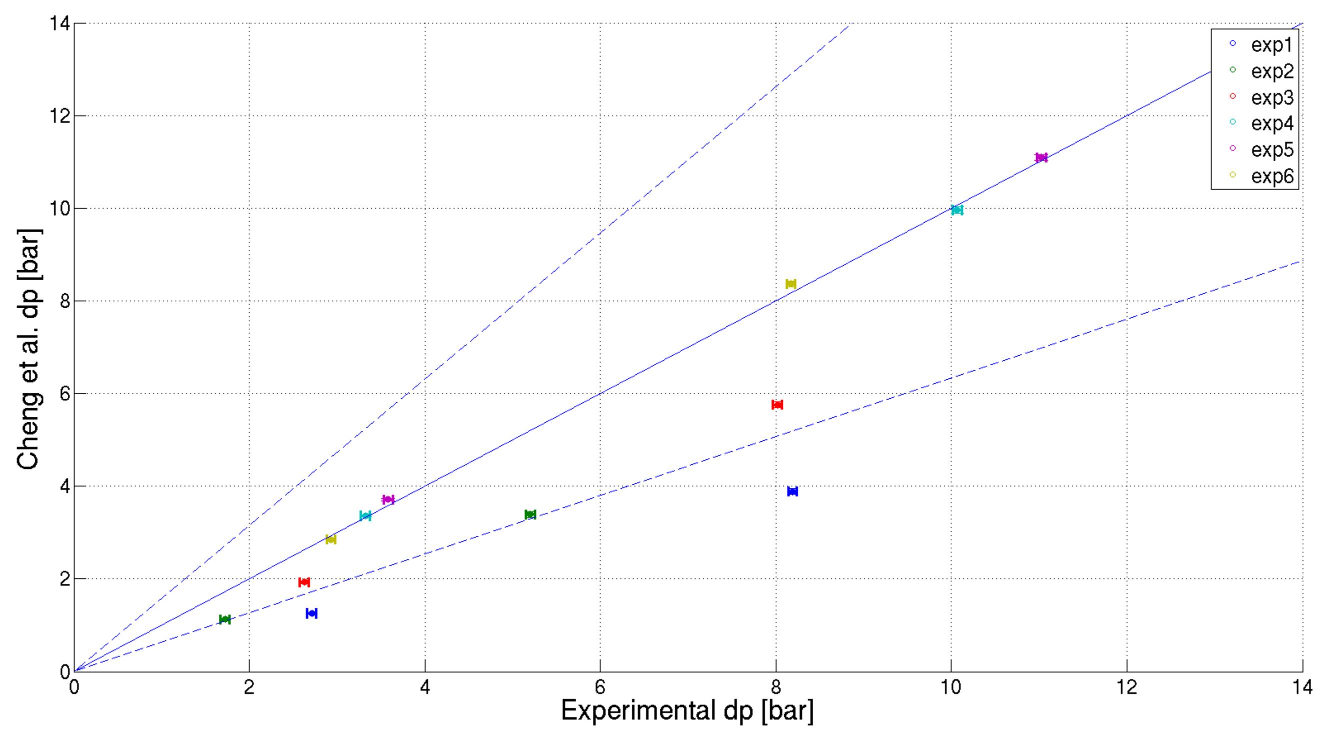
- Overall, the Friedel model performed best for our data
  - A large experimental database had a larger impact than CO_2-specific phenomenological modelling
  - The Friedel model gave a lower standard deviation on our data then on the large data collection employed by Friedel. This may indicate that the Friedel model is as suitable for CO_2 as for other fluids
- The Cheng *et al.* model performed best when only the high-flowing-vapor-fraction data were considered
- The homogeneous model underestimated all our pressure-drop data
- The friction-model-input sensitivity and the sensor uncertainty are small compared to the uncertainty in the friction models themselves
- It would be interesting to include more experimental data in the analysis
- It would be interesting to compare the models for more CCS-relevant conditions, i.e. for larger pipes and including impurities.



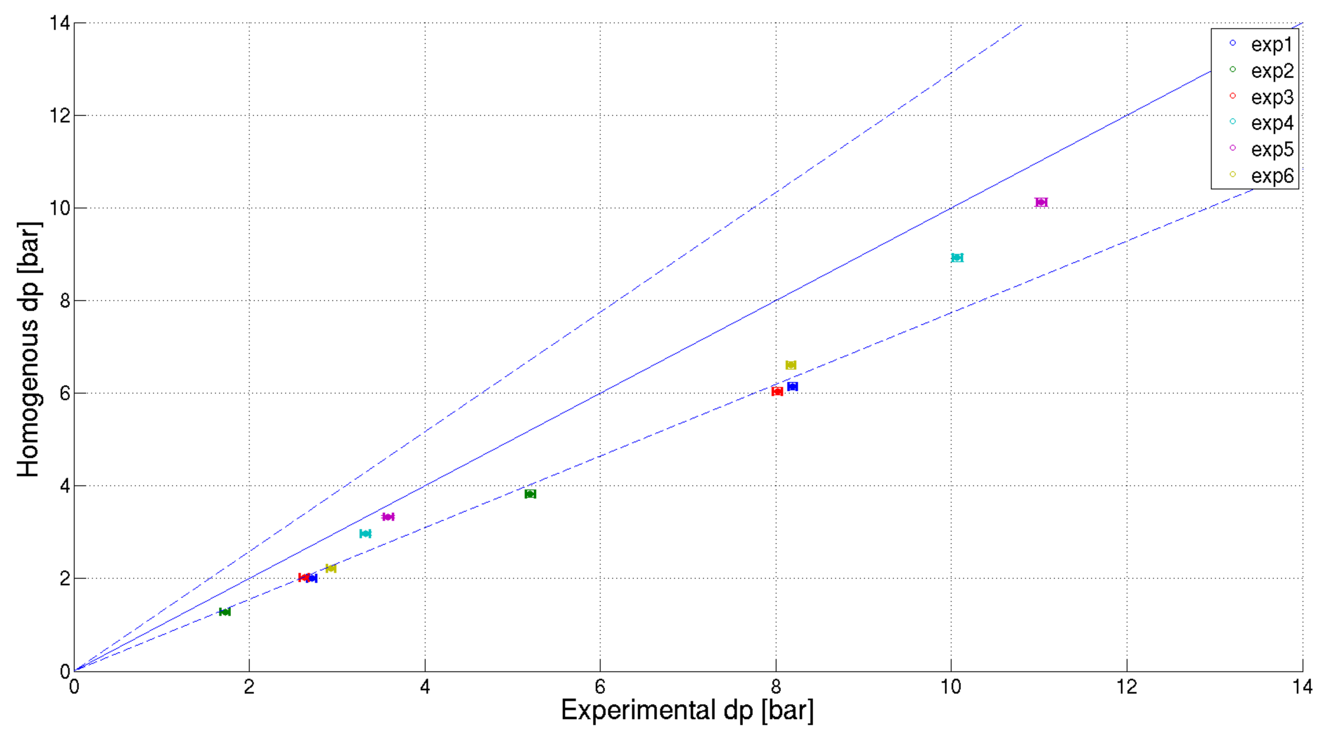
Flow patterns predicted by the Cheng *et al.* model for each experiment. S: Stratified, SW: Stratified-wavy, I: Intermittent, A: Annular, D: Dry-out.



(a) Friedel model



(b) Cheng *et al.* model



(c) Homogeneous-flow model

Comparison between experimental and calculated frictional pressure drop.

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