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ESTIMATING THE LINE PACKING TIME FOR PIPELINES TRANSPORTING CARBON DIOXIDE

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Estimating the line packing time for pipelines transporting carbon dioxide

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Estimating the line packing time for pipelines transporting carbon dioxide

Outline of the presentation

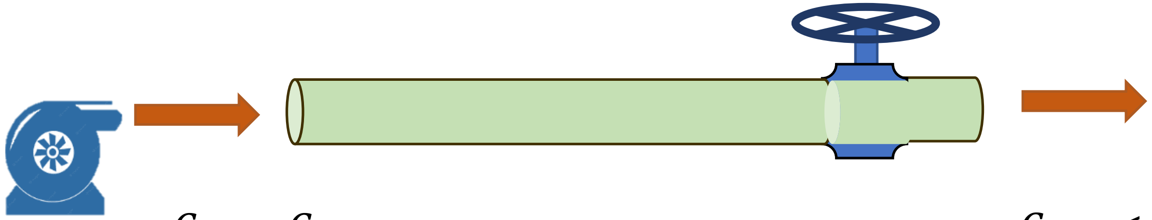
- Background and objectives
- The line packing flow model
- Estimating the line packing time
- Illustrative examples
- Conclusions

Background and Motivation

What is line packing?

*The "**line packing**" describes a method of control of pipeline operation by temporarily increasing the amount of fluid in the pipeline.* A pipeline in this case essentially works as a storage vessel for compressible fluid, and the inflow is allowed as long as the pipeline can withstand the increasing pressure.

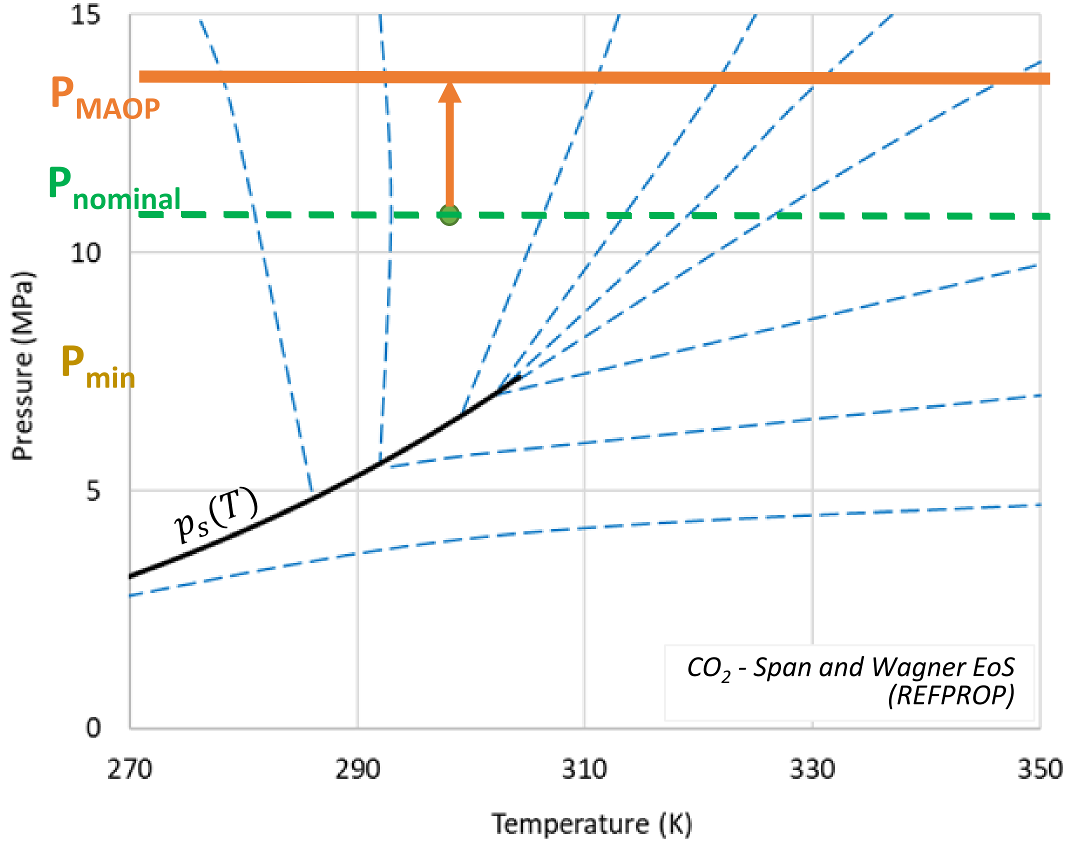
$G_{in} > G_o$ $G_{out} = G_o$



$G_{in} = G_o$ $G_{out} < G_o$

[G_o is the mass flow rate in the nominal operation]

[MAOP - Maximum Allowable Operation Pressure]



Background and Motivation

- In the **natural gas transmission and distribution pipelines**, line packing is routinely used to compensate for fluctuations in the gas supply and demand.
- In **CO_2 pipelines**, line packing can help to smooth the operation of pipelines and pipeline networks
- Experience from the natural gas industry is not always transferrable because dense-phase/ liquid and supercritical **CO_2 fluid has properties** very different to those of natural gas.
- To account for **line packing in pipeline design**, two parameters are important: *line pack amount* and *line pack time*.

Definitions

- Line pack amount: $\Delta M_{LP} = M_{LP} - M_{LP,o} = V_{pipe}(\bar{\rho} - \bar{\rho}_o)$ ← *Can be estimated. Some correlations are available.*

$$M_{LP} = A_{pipe} \cdot \int_0^{L_{pipe}} \rho \, dx = A_{pipe} \, L_{pipe} \, \bar{\rho}$$

- Line pack time, t_{LP} : the duration that takes for pressure to reach the maximum level, usually associated with the Maximum Allowable Operating Pressure (p_{MAOP}) ← *No correlations have been developed. No experimental data available for CO_2.*

Recently, Aghajani et al (2017) performed flow simulations to determine line packing times for pipelines transporting *dense-phase CO_2*.

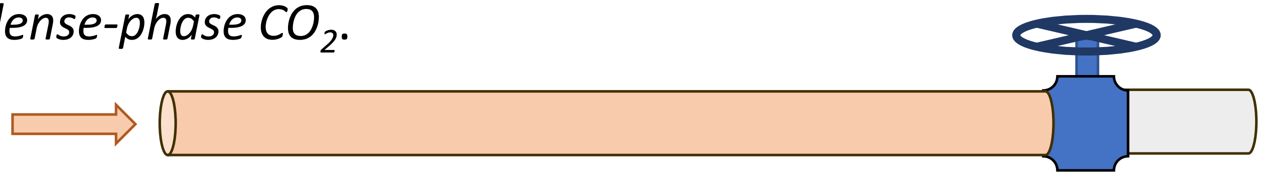
H. Aghajani et al (2017) "On the potential for interim storage in dense phase CO2 pipelines," Int. J. Greenh. Gas Control, vol. 66, pp. 276–287.

Line packing in CO_2 transportation pipelines

Aghajani et al (2017): **flow simulations** using OLGA package **to predict the line packing times** for pipelines transporting *dense-phase CO_2*.

- 81 cases were studied:

  Pipeline length: 50 .. 150 km
  Outer diameter: 457 .. 914 mm
  Wall thickness: 8 .. 20 mm
  Wall roughness: 0.0457 mm



Feed from compressor
G = 35 .. 150 kg/s
T_{in} = 30 °C

Pressure build-up
P_{MAOP} = 112 … 156 bar
T_{soil} = 5 °C

Isolation valve

- *Line packing time, t_{LP}, was found to be a function of:*

$$t_{LP} \sim V_{pipe}, p_{MAOP}, \frac{1}{G}, \frac{1}{p}$$

- *t_{LP}, was regressed using an ANN model*

H. Aghajani et al. — International Journal of Greenhouse Gas Control 66 (2017) 276–287

Table 3
Results of steady state and transient analysis for all pipeline designs considered to study the effects of pipeline dimensions and flow rate on line-packing times.

Inlet conditions					Steady state analysis		Transient analysis
					Stress criterion < 72% SMYS	Hydraulic criterion > 81.5 bara	
Pipeline no.	Outer diameter (D_o)/mm	Wall thickness (wt)/mm	Length /km	Flow rate (kg/s)	%SMYS	Outlet pressure (P_o)/bara	Linepacking time/s
1	457	8	50	150	69.8	105.6	135
			100	150	69.8	101.3	335
			150	150	69.8	97.5	557
			50	150	63.5	102.3	509
			100	150	63.5	95.0	1020
			...	...	...	...	...
80	457	11	150	150	52.3	113.3	3310
81	457	11	150	35	42.1	91.3	17,640

- *However, no correlation was proposed to describe the integral impact of the pipeline design and operating parameters on the line packing time.*

Aim and Objectives

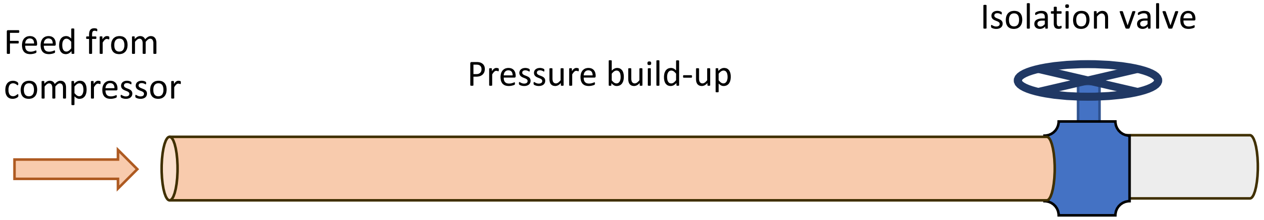
Aim: Quantifying the line packing time for pipelines transporting CO_2

Objectives:

- Verify a flow model against the results by Aghajani et al (2017).
- Analyse the model to obtain a correlation for estimating the line-packing time as a function of the pipeline design and operation parameters and the fluid properties.
- Estimate the line packing times for pipelines transporting gaseous CO_2.

Line-pack modelling

Two approaches can be used to predict transient flows in pipelines:



- Full model (resolving wide range of time scales) – Hyperbolic equations:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial \rho u}{\partial x} = 0 \\ \dfrac{\partial \rho u}{\partial t} + \dfrac{\partial \rho u^2}{\partial x} + \dfrac{\partial p}{\partial x} = -f \dfrac{\rho\, u\, |u|}{2D_{pipe}} \\ \dfrac{\partial E}{\partial t} + \dfrac{\partial u(E+p)}{\partial x} = \dfrac{4q_w}{D_{pipe}} - f \dfrac{\rho u^3}{2D_{pipe}} \end{cases}$$

- Reduced model (slow transients, isothermal/ adiabatic flow) – Parabolic equations:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial \rho u}{\partial x} = 0 \\ \dfrac{\partial p}{\partial x} = -f \dfrac{\rho\, u\, |u|}{2D_{pipe}} \end{cases}$$

Applied in the present study

Parabolic flow model

- Governing equations:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \dfrac{\partial \rho u}{\partial x} = 0 \\ \dfrac{\partial p}{\partial x} = -f \dfrac{\rho\, u\, |u|}{2D_{pipe}} \end{cases}$$

- Initial conditions (t = 0): ρu_o = const; $p_o(x)$; $T_o(x)$.

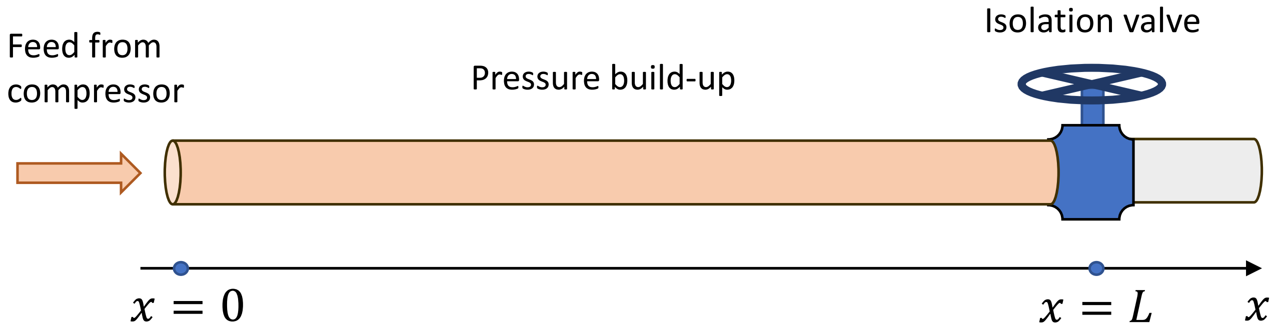
- Boundary conditions (t > 0): $\rho u(x=0) = \rho u_{in}$

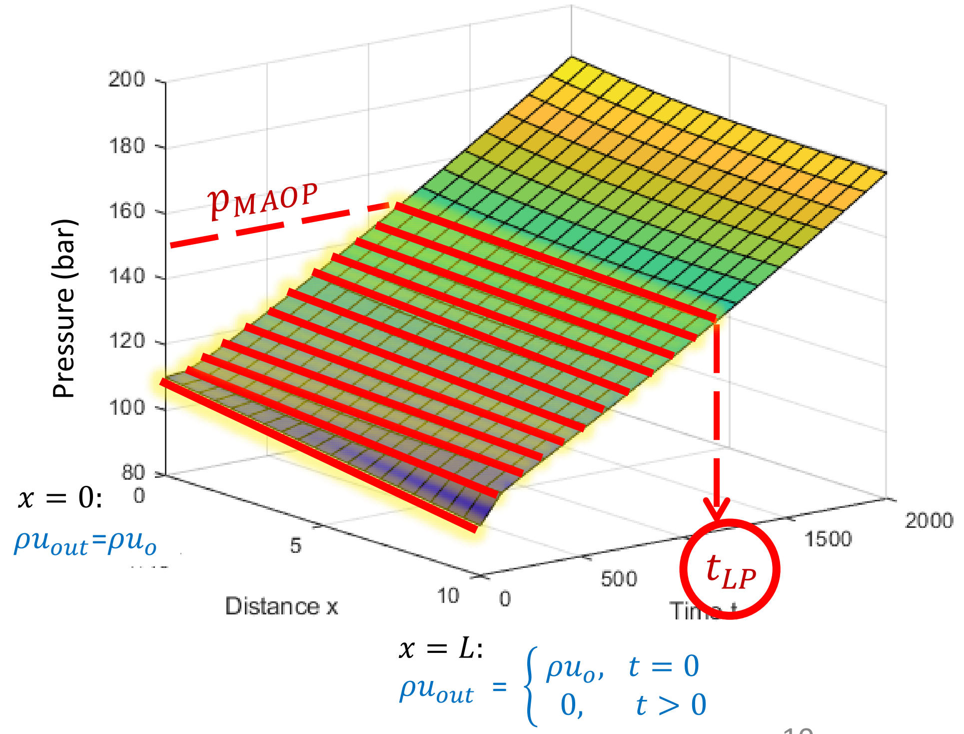
  $\rho u(x=L) = \rho u_{out}$

- Physical properties: (single phase) $\rho(p,T)$, $c_s(p,T)$, $\mu(p,T)$

  EoS by Span and Wagner (1996)

- Numerical solution: *The governing equations converted to a single PDE and solved in MatLab*





Results: The line packing times

- Reference data: *Aghajani et al (2017)*
- Present study: *The parabolic flow model slightly under-predicts the line packing times*

H. Aghajani et al. | International Journal of Greenhouse Gas Control 66 (2017) 276–287

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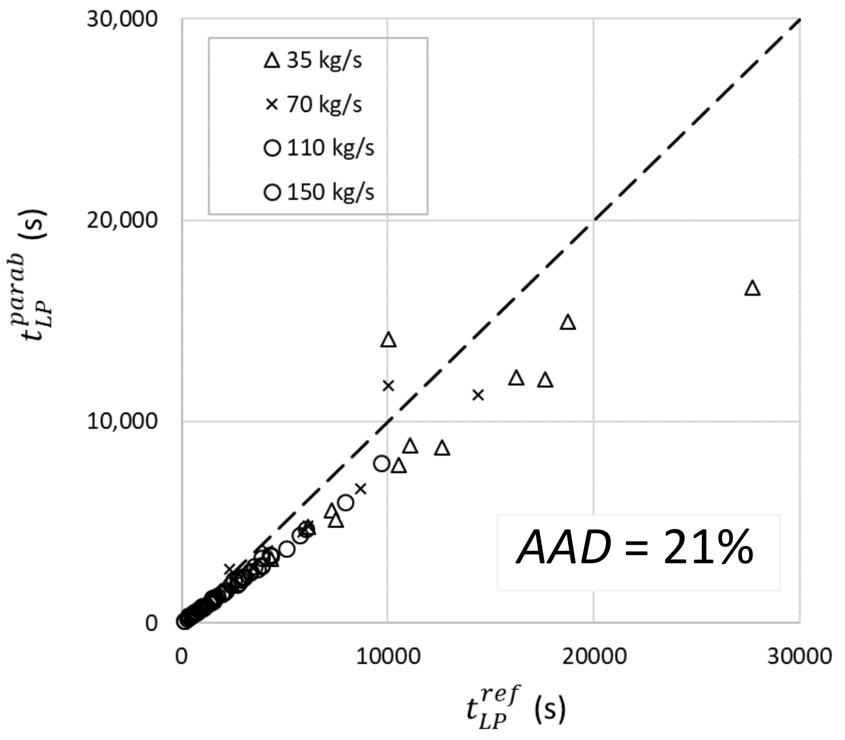


Absolute average deviation:

$$AAD = \sum_{i=1}^{N=81} \left| 1 - \frac{t_{LP,i}}{t_{LP,i}^{ref}} \right| \times 100\%$$

Analysis of the flow model

- Integration of the mass conservation equation over the pipe length and the line packing time t_{LP}:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = 0$$

$\iint dtdx$

$$L_{pipe} \int_0^{t_{LP}} \frac{\partial \bar{\rho}}{\partial t} dt \approx -t_{LP} \int_0^{L_{pipe}} \frac{\partial \rho u}{\partial x} dx$$

$$\underbrace{V_{pipe}(\bar{\rho}_{LP} - \bar{\rho}_o)}_{\Delta M_{LP}} \approx \underbrace{t_{LP}(\rho u_{in} - \rho u_{out}) A_{pipe}}_{\Delta G}$$

ΔM_{LP} *Line-pack amount*

ΔG *Cumulative mass flowrate into the pipeline*

Expressing the density variations in terms of pressure:

$$(\bar{\rho}_{LP} - \bar{\rho}_o) \approx \frac{\tilde{\bar{\rho}}}{\tilde{\bar{\kappa}}_x} \cdot \frac{(\bar{p}_{LP} - \bar{p}_o)}{\tilde{\bar{p}}}$$

The process-dependent expansion coefficient:

$$\kappa_x \equiv \frac{\rho}{p} \left(\frac{\partial p}{\partial \rho} \right)_x$$

Average pressure and density: $\tilde{\bar{p}}, \tilde{\bar{\rho}}$

Line-packing time:

$$t_{LP} = \frac{\tilde{\bar{\rho}}}{\tilde{\bar{\kappa}}_x} \cdot \frac{V_{pipe}}{\Delta G} \cdot \frac{(\bar{p}_{LP} - \bar{p}_o)}{\tilde{\bar{p}}}$$

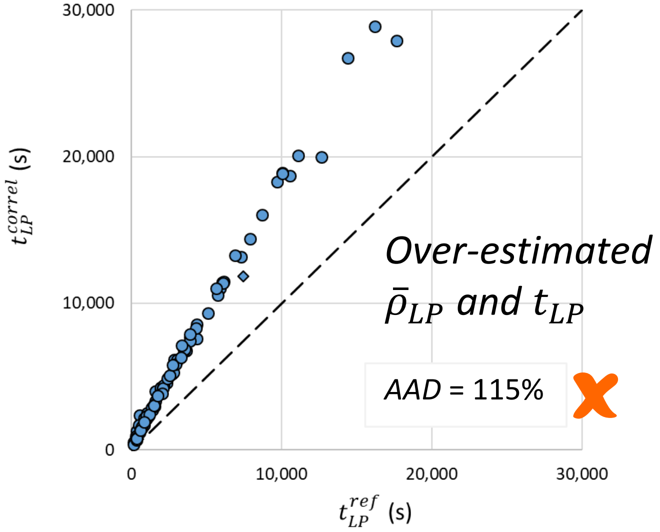
new term

desribing the trends reported by Aghajani, et al (2017)

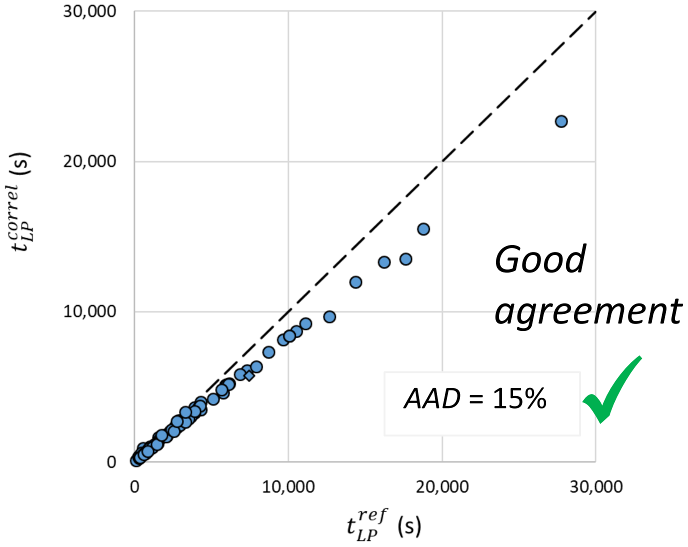
Constructing the correlation for the line packing time

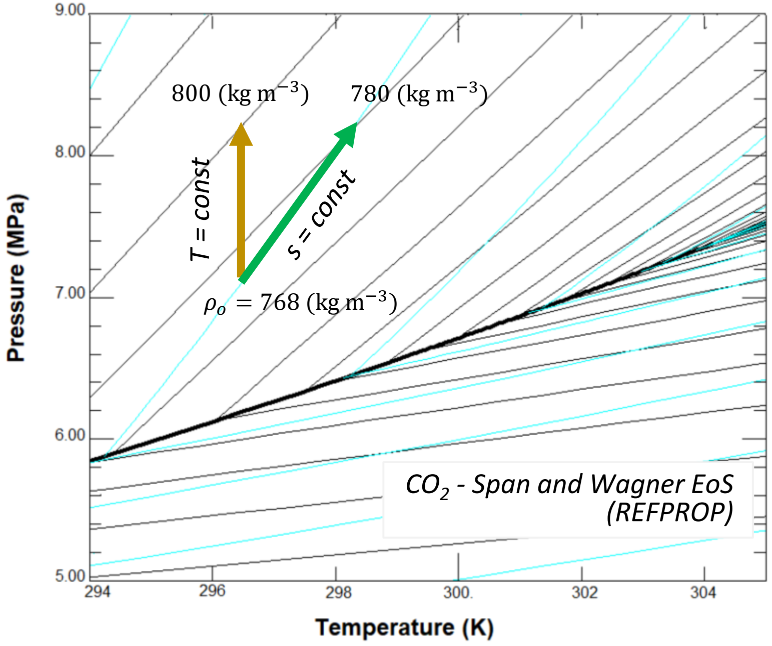
Line-packing time: $t_{LP} = \frac{\rho_o}{\kappa_{x,o}} \cdot \frac{V_{pipe}}{G_{in}} \cdot \frac{(\bar{p}_{LP} - \bar{p}_o)}{\bar{p}_o}$

Isothermal flow:



Isentropic flow:





Isentropic expansion coefficient:

$$\kappa_s \equiv \frac{\rho}{p}\left(\frac{\partial p}{\partial \rho}\right)_s \equiv \frac{\rho\, c_s^2}{p}$$

Note: $\bar{p}_o$ and $\bar{T}_o$ can be obtained using steady-state flow models.

Results: Line packing time – impact of operating pressure/ fluid phase

Scenario: A 50% increase in the inlet mass flow rate, keeping the outlet flowrate unchanged.

$D = 1\ (\mathrm{m})$

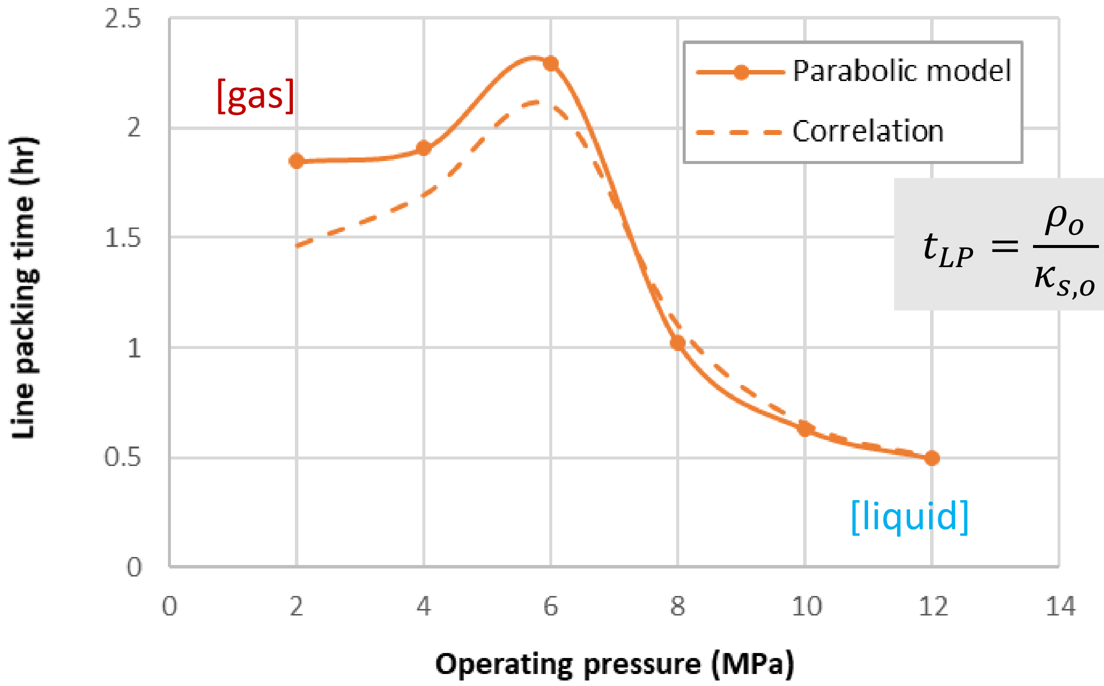
$L = 33\ (\mathrm{km})$

$p_{in} = 2\ (\mathrm{MPa}) \dots 12\ (\mathrm{MPa})$
[gas] ... [liquid]

$G_o = \rho\, u\, A_{pipe} = 150\ (\mathrm{kg\, s^{-1}})$

$T_o = 303\ (\mathrm{K})$

$p_{MAOP} = p_{in} + 1\ (\mathrm{MPa})$



$$t_{LP} = \frac{\rho_o}{\kappa_{s,o}} \cdot \frac{V_{pipe}}{\Delta G} \cdot \frac{(p_{MAOP} - p_o)}{p_o}$$

Pipelines transporting gas-phase CO_2 have longer t_{LP}, offering greater operation flexibility – permitting longer periods (several hours) of temporary increase in the inlet flowrate and disruptions at the pipeline discharge end.

Results: Line packing time – impact of temperature

Scenario: Closure of the discharge valve.

$D = 1$ (m)

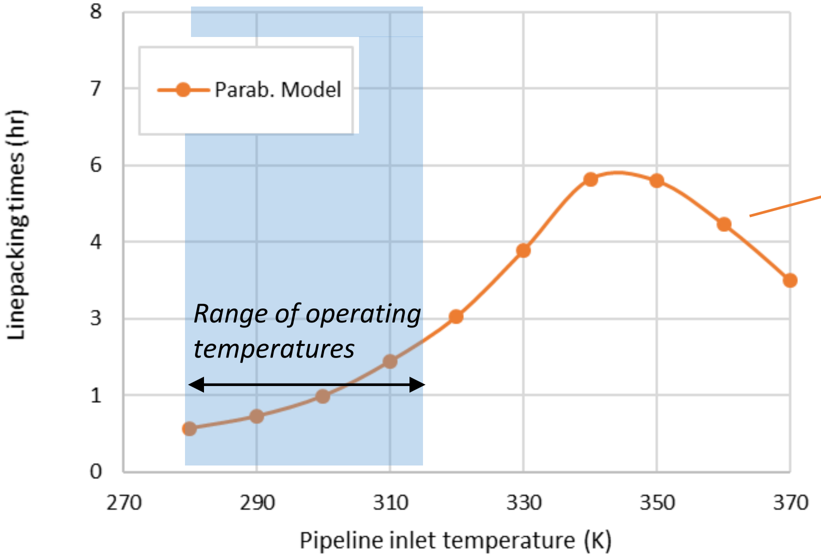
$L = 80$ (km)

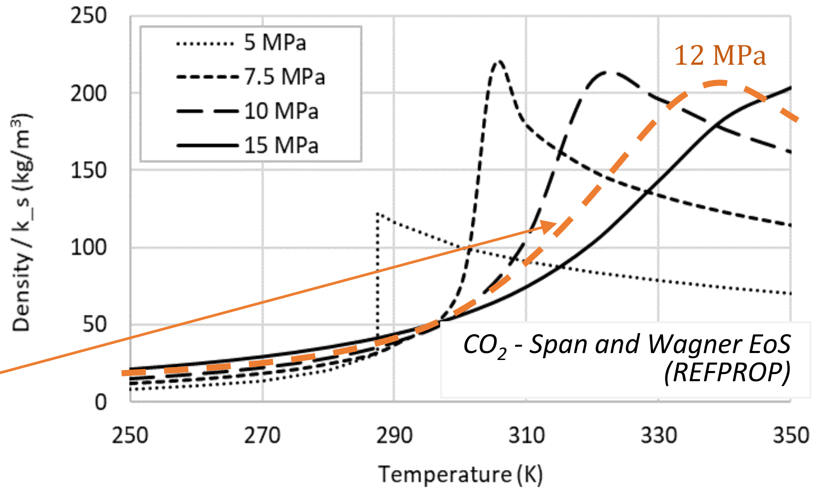
$p_{in} = 12$ (MPa)

$G_o = 50$ (kg s^{-1})

$T_o = 280$ (K) … 370 (K)

$p_{MAOP} = p_{in}$ + 1 (MPa)





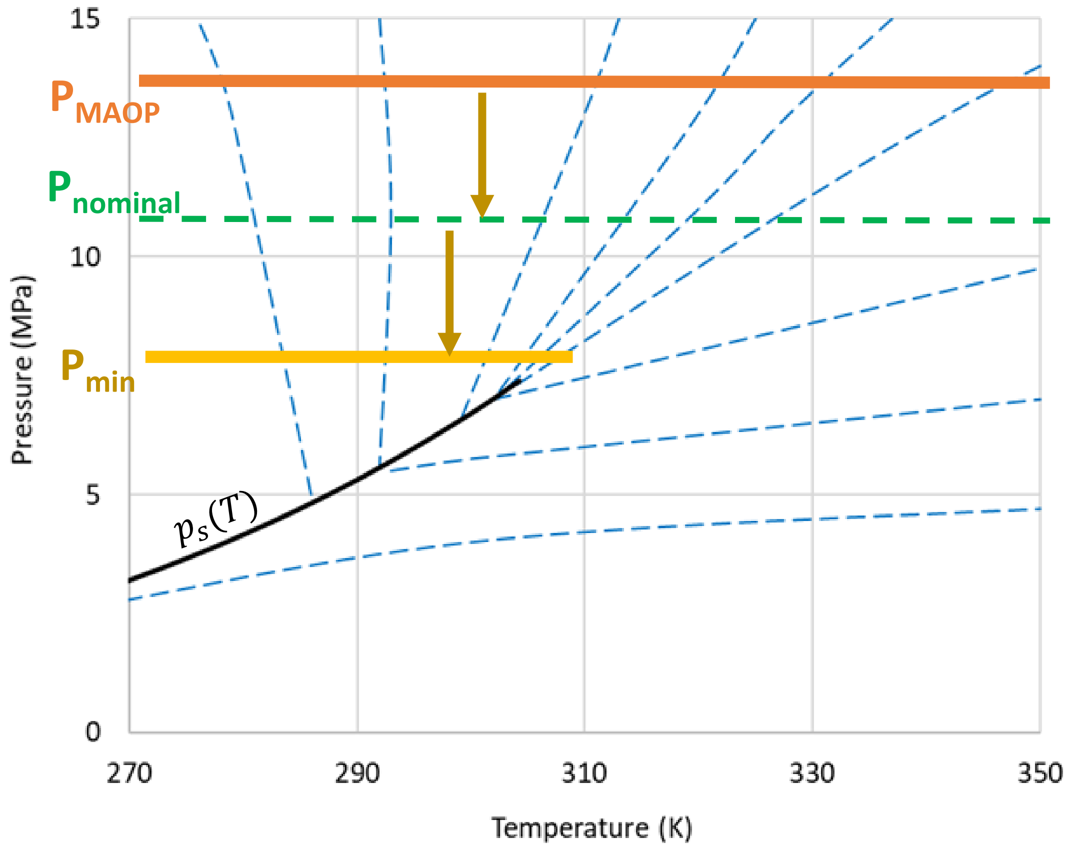
$$t_{LP} = \frac{\rho}{\kappa_s} \cdot \frac{V_{pipe}}{G} \cdot \frac{(\bar{p} - p_o)}{p_o}$$

The line packing time peaks at temperatures in the supercritical phase region (around the critical isentrope of CO_2), which are outside the expected nominal conditions of pipeline operation.

Pipeline drafting

- The model developed can be adopted to **drafting** operation when the pipeline discharges the fluid and pressure is allowed to drop, e.g., from MAOP to nominal operating pressure or below.

- **Scenario:** Unbalanced discharge of fluid upon the inlet compressor trip.



- Drafting time can be defined as the time it takes for pressure to get to the minimum operating pressure. It can be estimated as:

$$t_{draft} = \frac{\rho_o}{\kappa_{s,o}} \cdot \frac{V_{pipe}}{\Delta G} \cdot \frac{(p_o - p_{min})}{p_o}$$

Summary and conclusions

- **A simple correlation predicting the line packing time was derived**
  - ✓ Accounting for the design/operation parameters and physical properties of the fluid.
  - ✓ **It is generic, consistent with the estimate of the line pack amount**
  - ✓ It is applicable to other fluids and operation conditions, although, the accuracy may deteriorate if the physical properties change significantly during the line packing.
  - ✓ It can be adopted to **estimate the pipeline drafting times**.
- **Transporting CO_2 in gas phase offer better operational flexibility than transporting dense phase CO_2**. Further study is needed to examine the line packing for supercritical CO_2.
- Further studies are needed to **experimentally validate the line packing models** for wide range of CO_2 transport conditions.
- **The developed line pack correlation** and **the parabolic flow model** can become useful in design of CO_2 transportation pipes and pipeline networks **operating in transient regimes**.

Thank you

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