CO_2QUEST

CO_2 compression and flow in transportation networks

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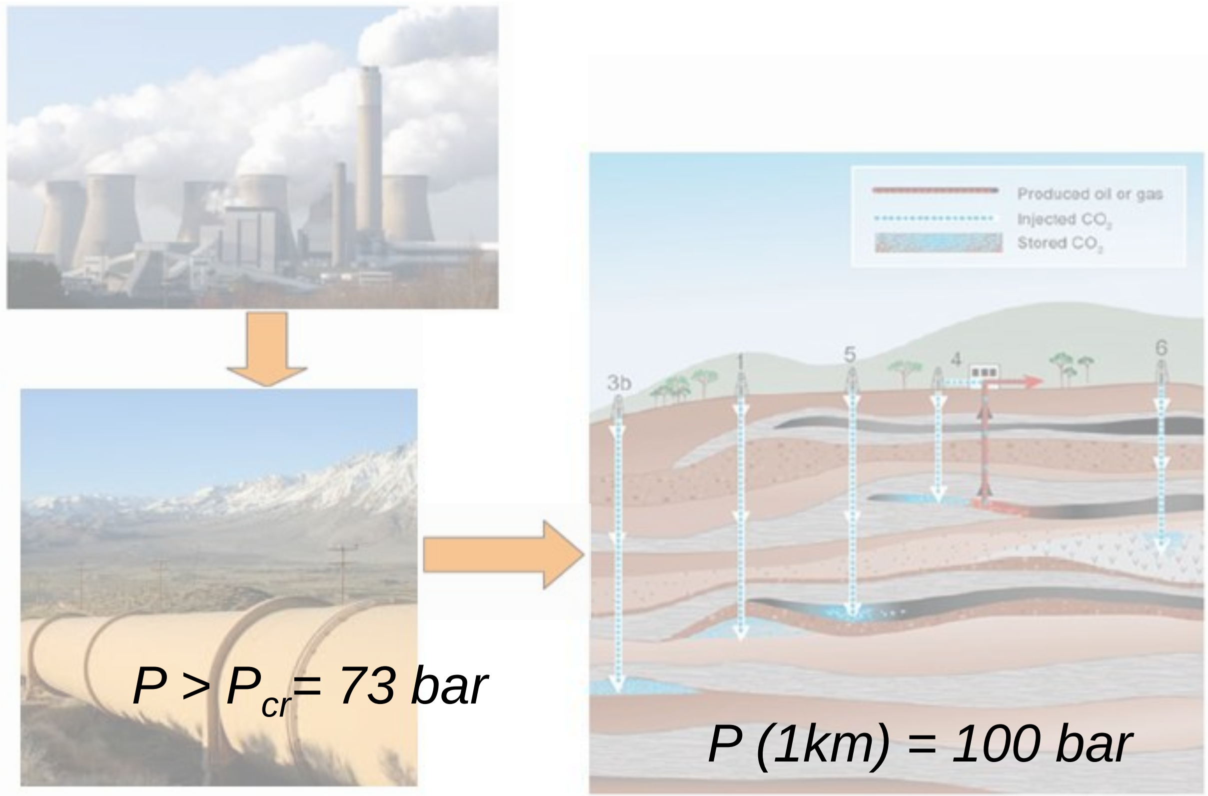
CO_2 compression and transportation in CCS



Transportation and injection into geological formations of **large amounts** of CO_2 requires compression of captured stream to dense-phase or supercritical states

CO_2 pipeline transportation and compression costs

In case of CO_2 sequestration, where CCS brings no direct commercial benefits (unlike in EOR projects), the question is

What are the costs of CO_2 compression and transportation?

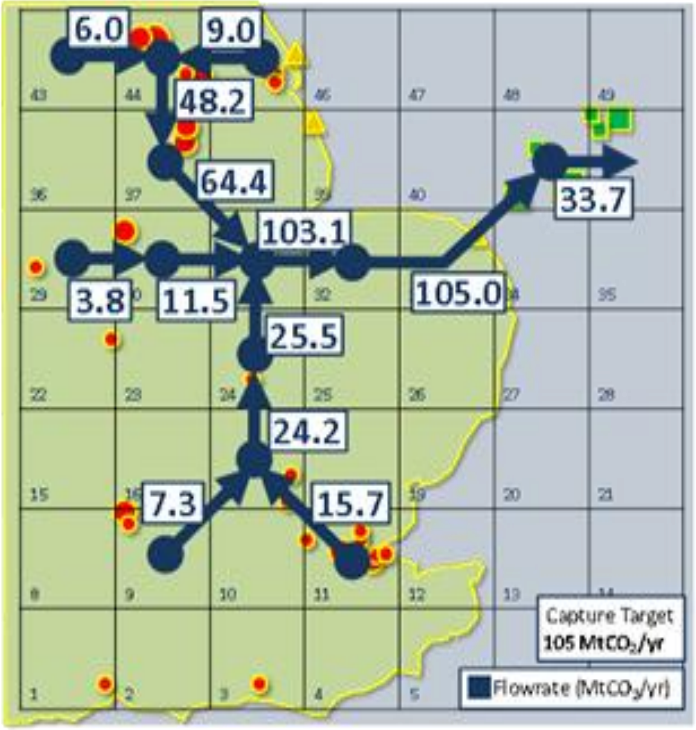
- 100 MWe coal-fired power plant emits ~ 1Mt CO_2 per year
- Compression of 1 Mt/a CO_2 from 1 to 150 bar pressure: ~ 10 MW

Hence, the CO_2 compression penalty is ~ 10%

Any improvements in design and operation of compression, transportation and injection will help to reduce the cost of the technology

CO_2 pipeline transportation

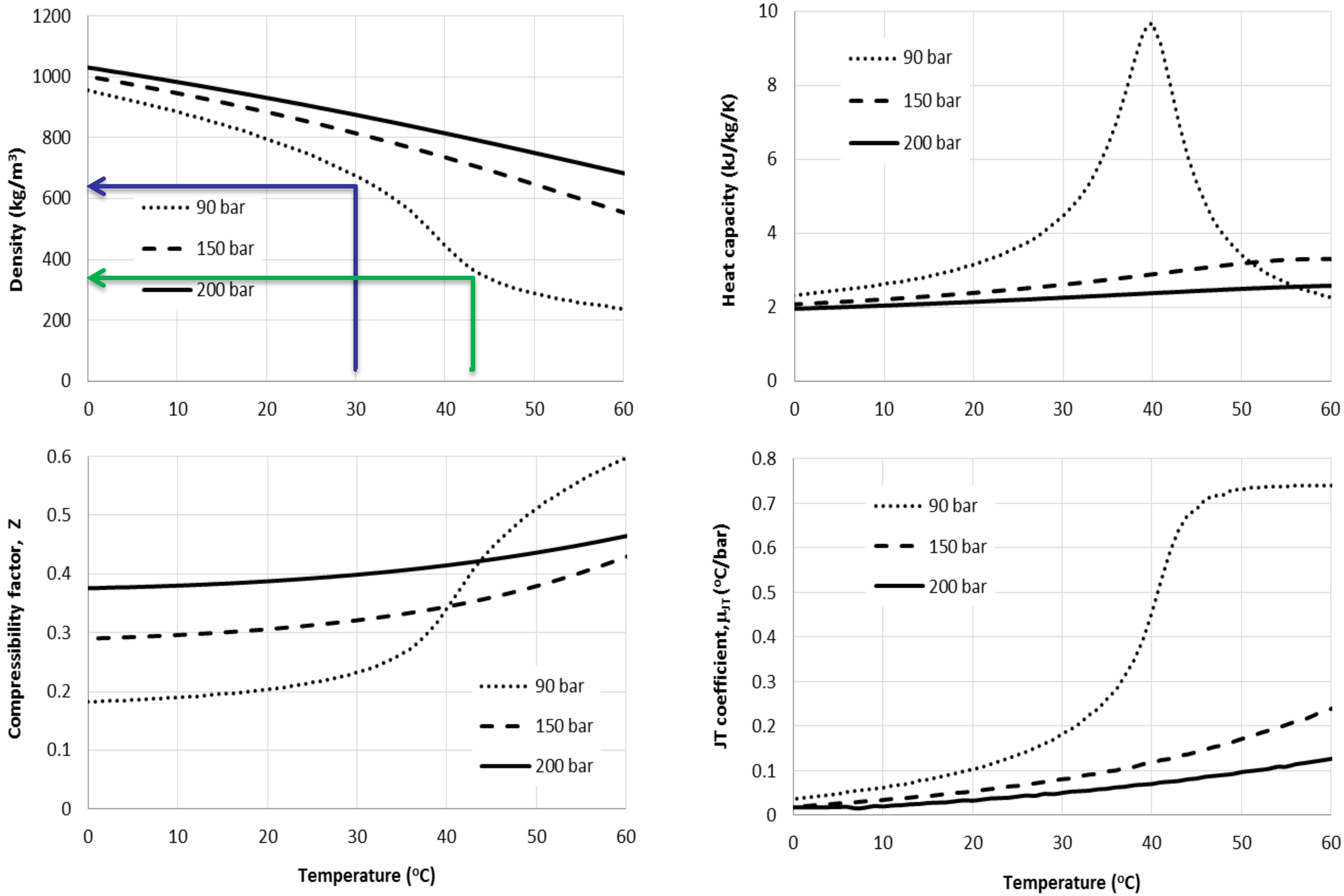
In case of a long-distance multi-source CO_2 pipeline transmission, the costs of compression are partially caused by hydraulic losses in the network.



As such, designing such networks requires **thermo-hydraulic** modelling of CO_2 flow in the pipeline segments

Engineering thermo-hydraulic models are commonly used in the design of ***gas*** and ***liquid*** transportation pipelines, **but their validity for *supercritical* CO_2 is unclear**

Physical properties of supercritical CO2



Objective of the study

Assessment of ***engineering*** *thermo-hydraulic models* against more rigorous, but computationally demanding, *differential equation model (**1D model**)* for prediction of pressure drop and temperature variation in pipelines transporting supercritical CO_2

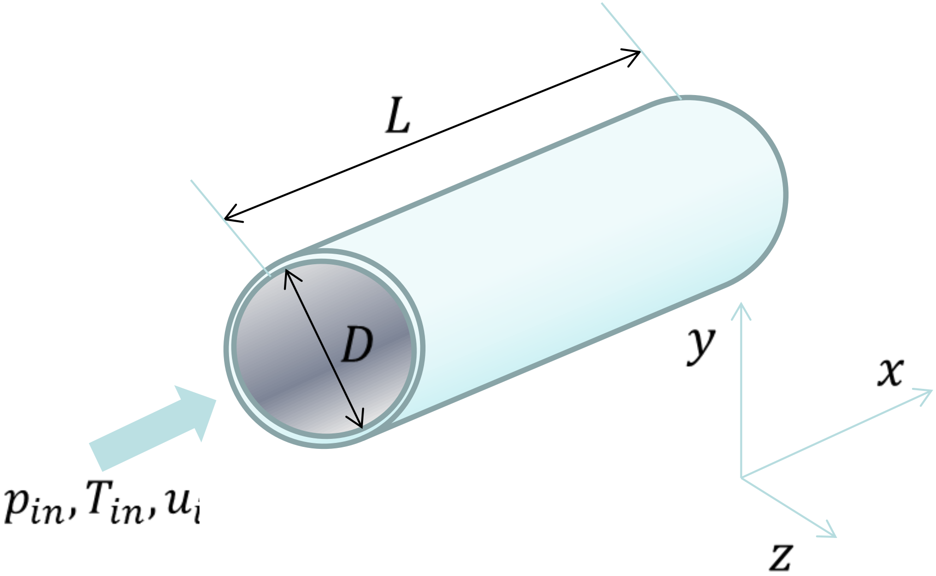
1D flow model

Continuity, momentum and energy equations:

$$\frac{d\rho u}{dx} = 0$$

$$\frac{d\rho u^2}{dx} = -\frac{dp}{dx} - f\frac{\rho u^2}{2D}$$

$$\frac{d\rho u(h + \frac{1}{2}u^2)}{dx} = \frac{4q_w}{D} + f\frac{\rho u^3}{2D}$$



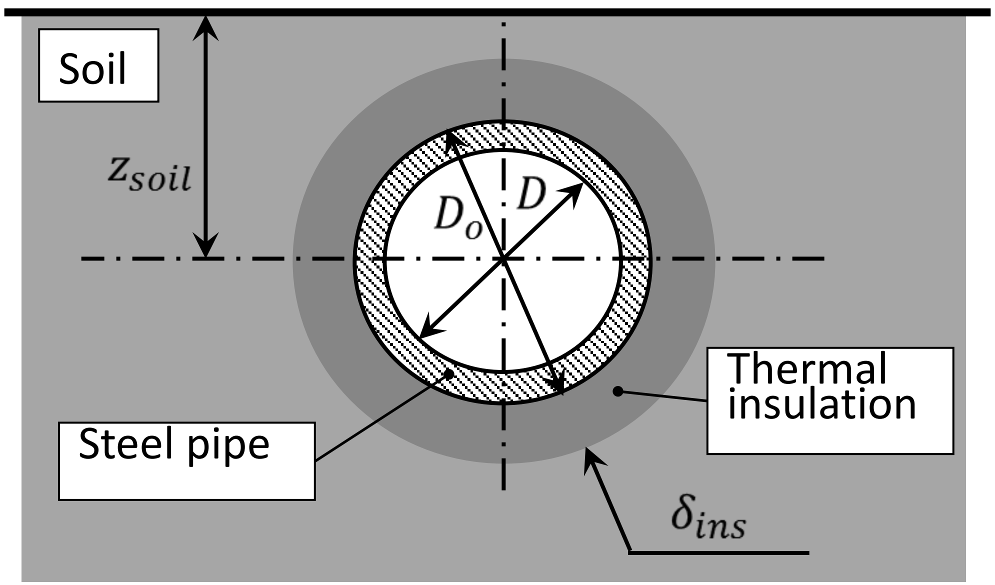
Darcy friction factor for turbulent flow (Colebrook & White):

$$f = 0.25\left[lg\left(\frac{\epsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^{-2}$$

Heat flux at the pipe wall:

$$q_w = \alpha\,(T_f - T_a)$$

Pipeline heat exchange model



Wall heat flux:

$$q_w = \alpha\,(T_f - T_a)$$

Overall heat transfer coefficient:

$$\alpha = \left[\frac{1}{\alpha_f} + \frac{D}{2\,\lambda_w}\ln\left(\frac{D_o}{D}\right) + \frac{D}{2\,\lambda_s}\ln\left(\frac{z_s}{D}\right) + \frac{1}{\alpha_a}\frac{D}{2\,z_s}\right]^{-1}$$

Forced convection turbulent heat transfer (Dittus-Boelter correl.): $\alpha_f = 0.023 Re^{0.23} Pr^{0.4}\frac{\lambda_f}{D}$

Engineering thermo-hydraulic models

Engineering thermo-hydraulic models can be viewed as ***integral*** versions of the 1D flow model, i.e. obtained upon integration of the 1D model differential equations along the pipe length

- Hydraulic part – pressure drop along the pipeline
- Thermal part – temperature change in the flow along the pipeline

Integral models – Pressure drop

Model 1: Non-isothermal compressible flow

$$p_{in} - p_{out} = \underbrace{\left(\frac{\overline{\rho u}^2}{\bar{p}}\right)\overline{\left(\frac{p}{\rho}\right)}\frac{\bar{f}}{2}\frac{L}{D}}_{\Delta p_f} + \underbrace{\left(\frac{\overline{\rho u}^2}{\bar{p}}\right)\overline{\left(\frac{p}{\rho}\right)} ln\left(\frac{p_{in}}{p_{out}}\right)}_{\Delta p_c} - \underbrace{\left(\frac{\overline{\rho u}^2}{\bar{p}}\right)\left(\frac{p_{in}}{\rho_{in}} - \frac{p_{out}}{\rho_{out}}\right)}_{\Delta p_\rho}$$

Model 2: Isothermal compressible flow

$$\frac{p_{in}^2 - p_{out}^2}{2\overline{\rho u}^2} = \bar{Z}RT\left[\frac{\bar{f}}{2}\frac{L}{D} + ln\left(\frac{p_{in}}{p_{out}}\right)\right]$$

Model 3: Isothermal incompressible flow – Darcy-Weisbach equation

$$p_{in} - p_{out} = \bar{f}\frac{\overline{\rho u}^2}{2\bar{\rho}}\frac{L}{D}$$

Integral models – Temperature change

Model A: Flow with heat transfer and expansion cooling

$$\overline{\rho u}\frac{dh}{dx} = \frac{4q_w}{D}; \longrightarrow T_{in} - T_{out} = \underbrace{\overline{\mu_{JT}}(p_{in} - p_{out})}_{\Delta T_{JT}} + \underbrace{\frac{-4\, q_w}{\overline{\rho u}\; \overline{c_p}}\frac{L}{D}}_{\Delta T_{qw}}$$

Model B: Flow with heat transfer, NO expansion cooling

$$T_{out} = \bar{T}_a + (T_{in} - \bar{T}_a)\exp\left(-\frac{4\bar{\alpha}}{\overline{\rho u}\; \overline{c_p}}\frac{L}{D}\right)$$

Model C: Isothermal flow

$$T_{out} = T_{in}$$

Integral thermo-hydraulic models

Hydraulic model \ Thermal model		A	B	C
		Heat transfer + expansion cooling	***Heat transfer NO expansion cooling***	***T = const***
1	***Compressible non-isothermal flow***	**Model 1A**	**Model 1B**	
2	***Compressible isothermal flow***			**Model 2C**
3	***Incompressible flow, Darcy-Weisbach Eq.***	**Model 3A**	**Model 3B**	**Model 3C**

Assessment of the integral models

Integral models

Δp_{1D}

$T_{out,1D}$

vs

1D model

Δp

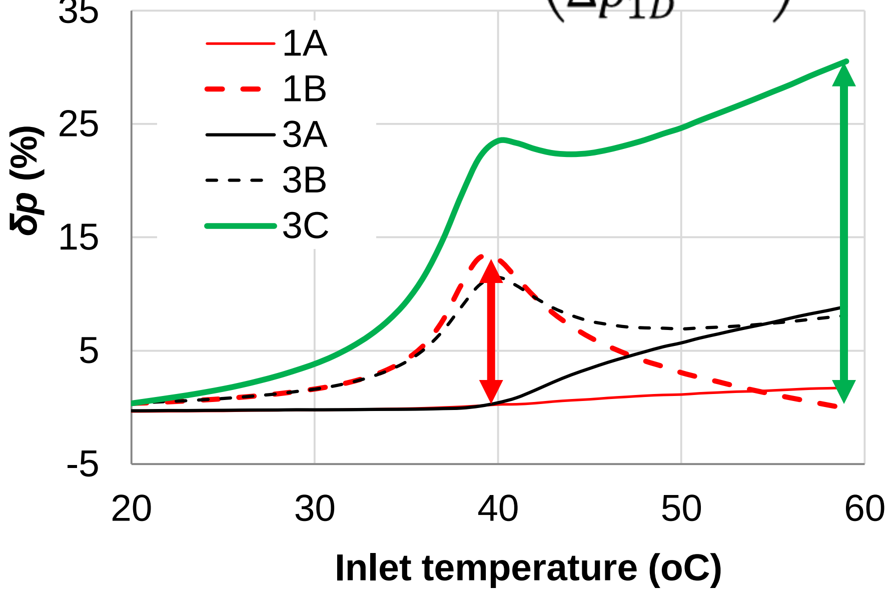
T_{out}

<u>Flow conditions:</u>

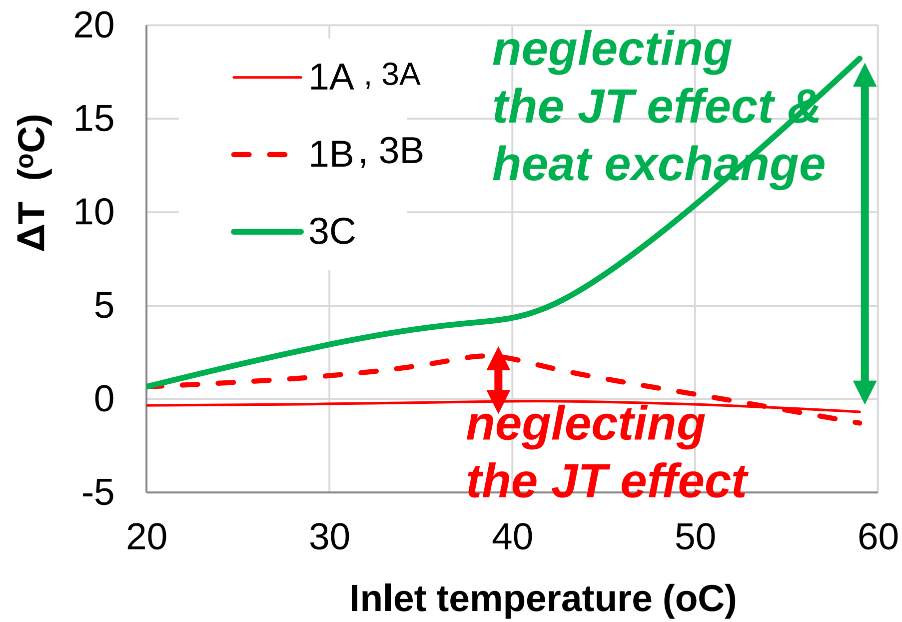
- Pipeline internal dia: $D = 0.8$ m,
- Pipeline length: $L = 10 - 40$ km,
- Inlet pressure: $p_{in} = 90 - 200$ bar,
- Inlet temperature: $T_{in} = 20 - 60$ ^{o}C,
- Inlet velocity: $u_{in} = 3$ m/s,
- Insulation options: Above-ground/ Buried/ Insulated

Accuracy of the integral models

$$\delta p = 100\left(\frac{\Delta p}{\Delta p_{1D}} - 1\right)\%$$



$$\Delta T = T_{out} - T_{out,1D}$$



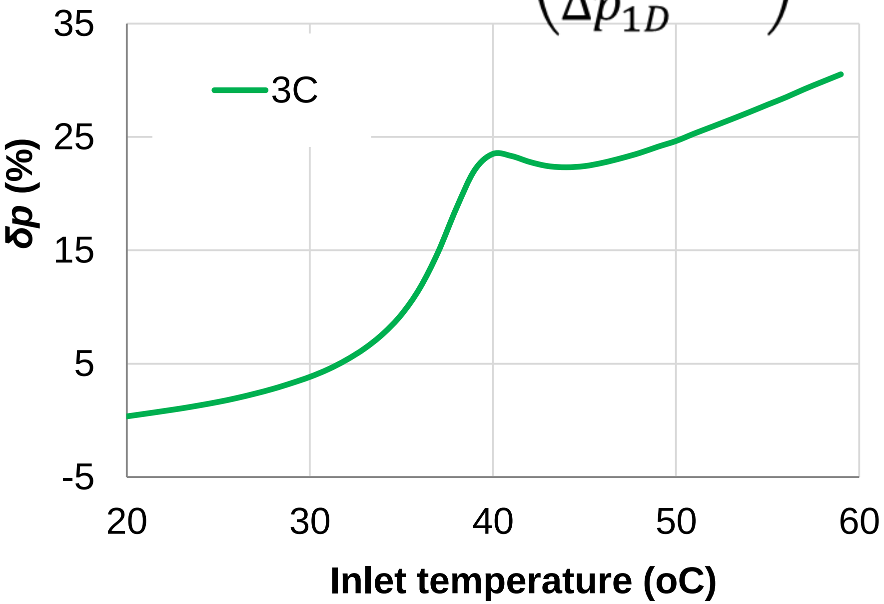
<u>Predictions by models 1A, 1B, 3A, 3B and 3C</u>

Above-ground pipeline (T_a=20ºC),

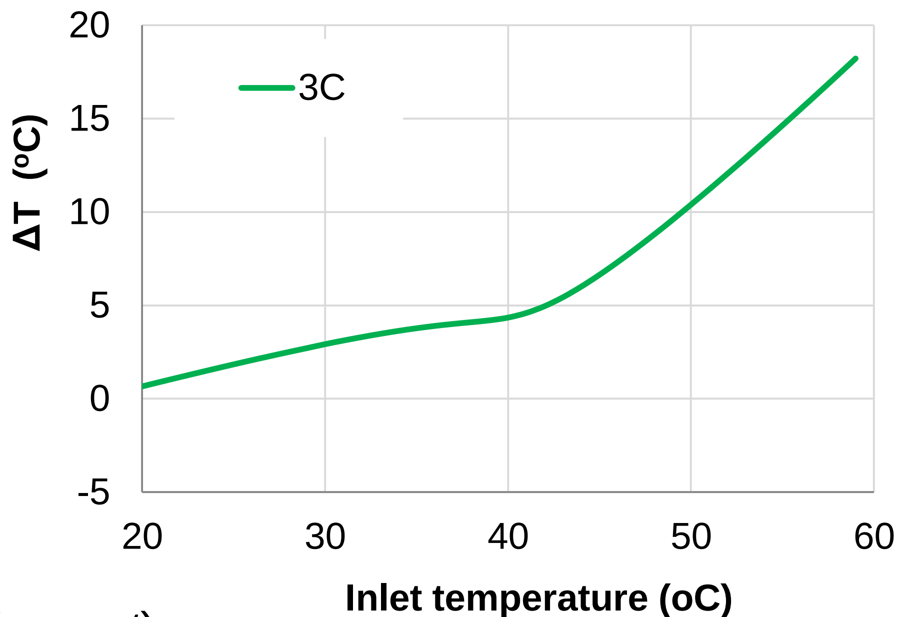
D = 0.8 m, L = 20 km, p_{in}= 90 bar, u_{in} = 3 m/s.

Accuracy of the integral models

$$\delta p = 100\left(\frac{\Delta p}{\Delta p_{1D}} - 1\right)\%$$



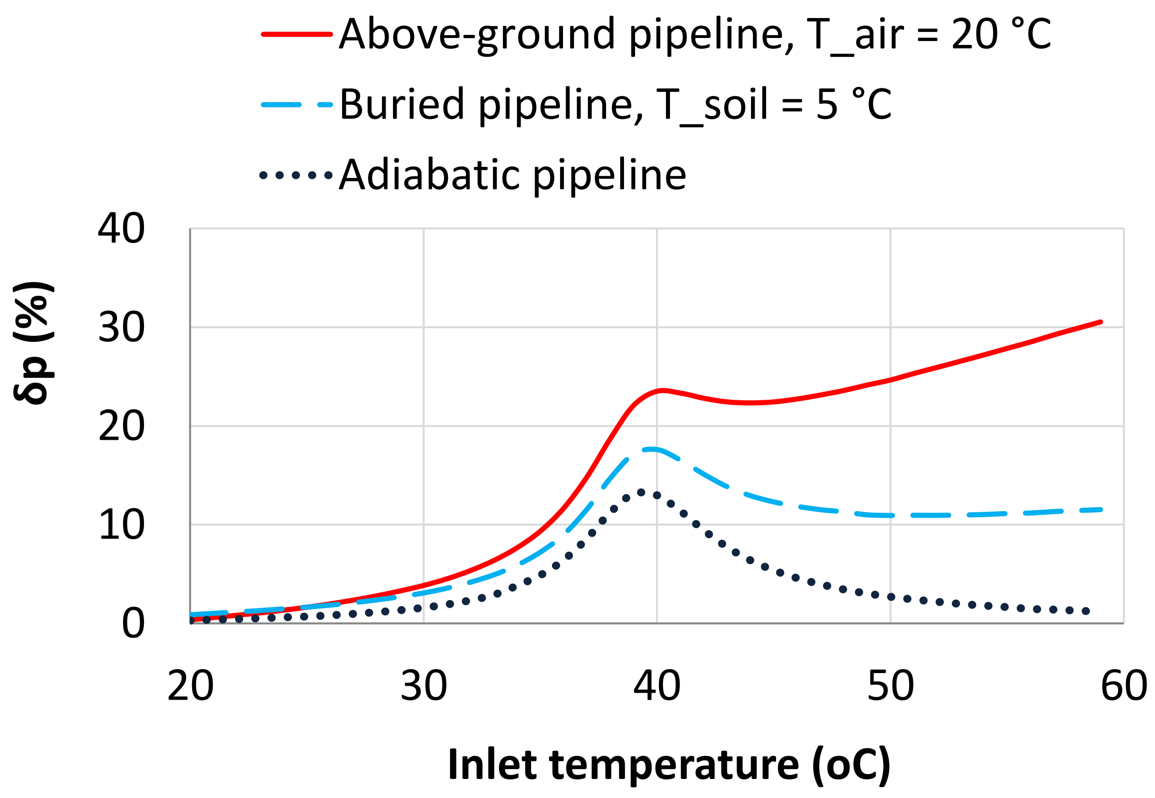
$$\Delta T = T_{out} - T_{out,1D}$$



Model 3C (*Darcy-Weisbach equation, T=const*)

$$p_{in} - p_{out} = f\frac{\overline{\rho u^2}}{2\rho}\frac{L}{D} \qquad \Delta p \sim \frac{1}{\rho}, \qquad \rho \sim \frac{1}{T}$$

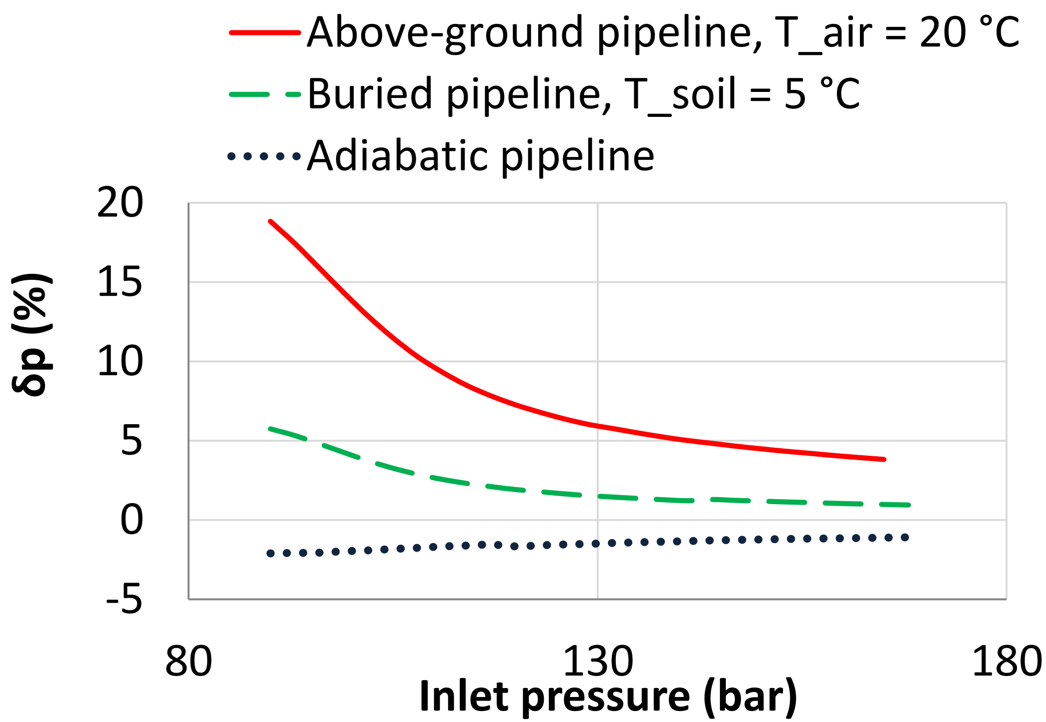
Effect of heat transfer



<u>Predictions by Model 3C</u>

D = 0.8 m, L = 20 km, p_{in}= 90 bar, u_{in} = 3 m/s.

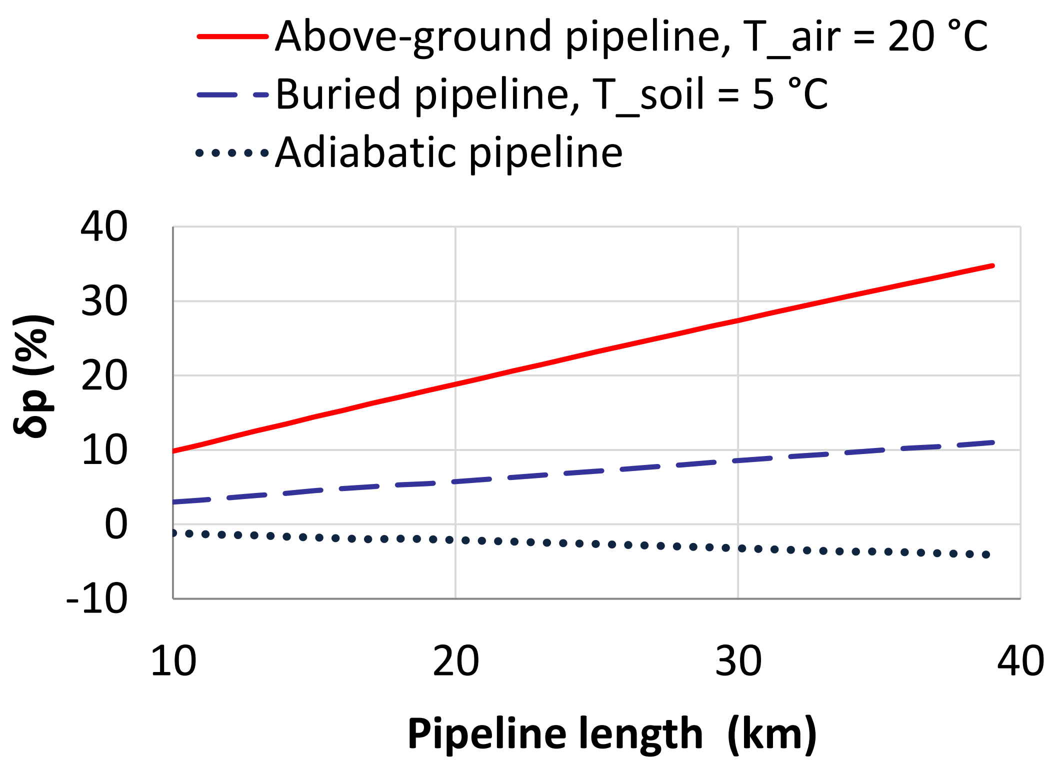
Effect of inlet pressure



Predictions by Model 3C

D = 0.8 m, L = 20 km, T_{in}= 40 ^oC, u_{in} = 3 m/s.

Effect of pipeline length



Predictions by Model 3C

D = 0.8 m, L = 20 km, p_{in}= 90 bar, u_{in} = 3 m/s.

Conclusions

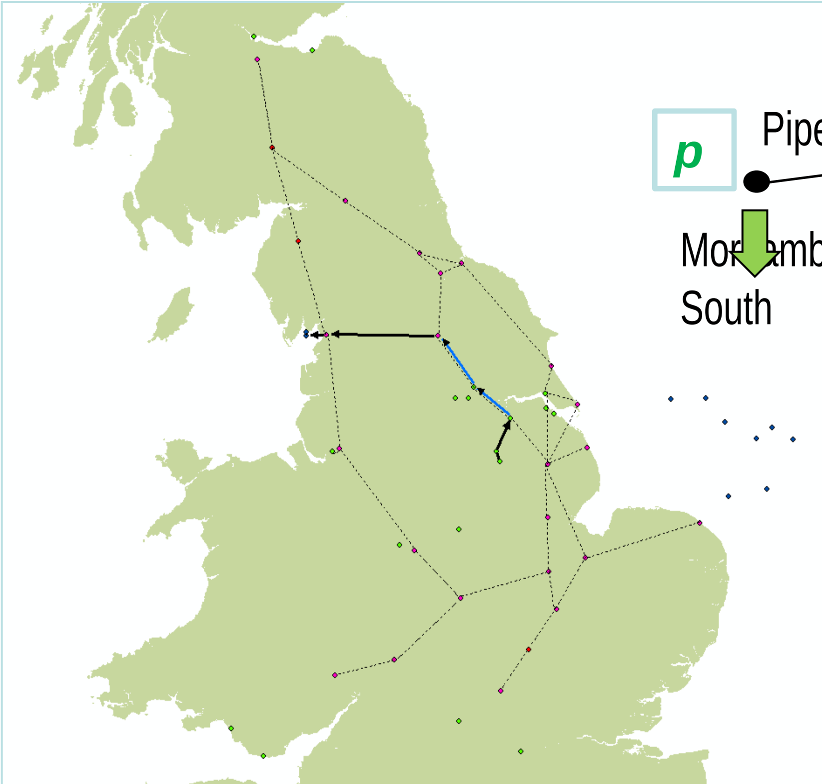
- **Isothermal flow assumption** => small errors in the flow *temperature*, which may translate into large errors in estimates of the fluid *density* and the pipeline *pressure drop*.
- **Overestimation of the pressure drop can lead to overdesign of the pipeline**, *e.g.*

200 km long pipeline, dp/dx = 0.5 bar/km:

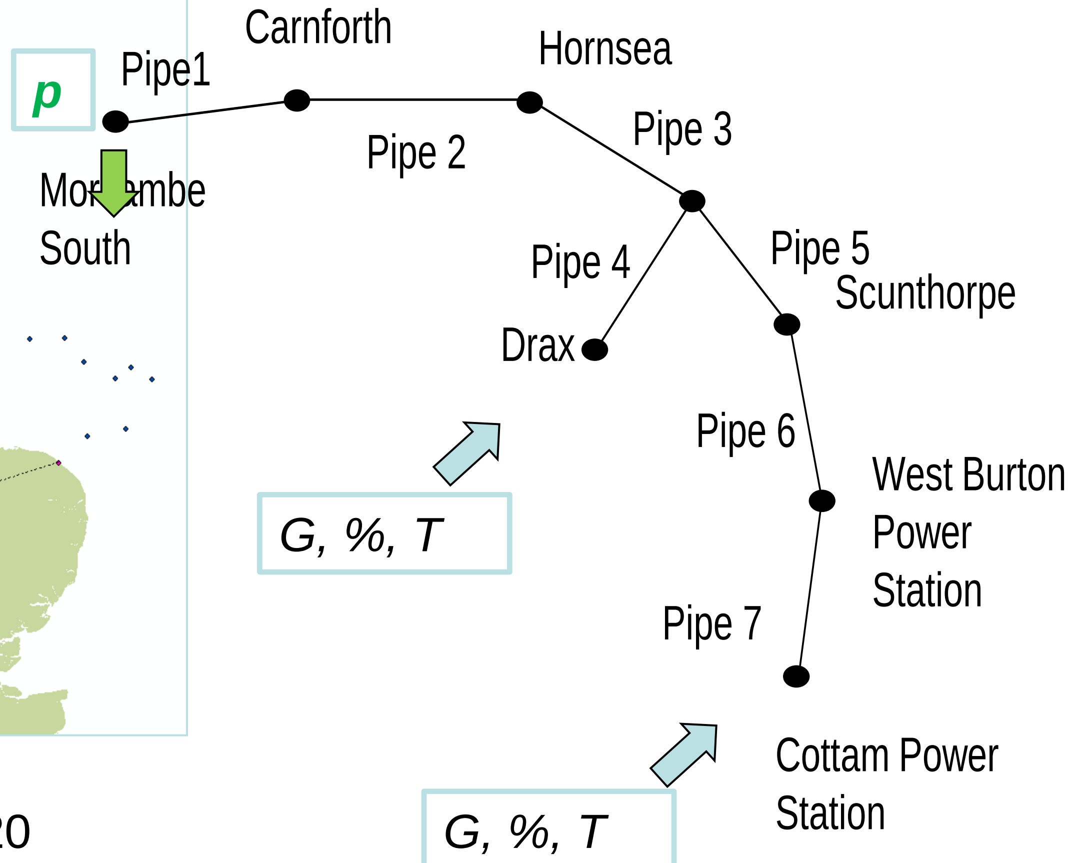
δp = 30% ⇔ 30 bar additional pressure drop,

⇔ **+1 booster pump station**

Pipeline networks flow model



UK CCS network 2010-2020



Schematic representation of the pipeline network

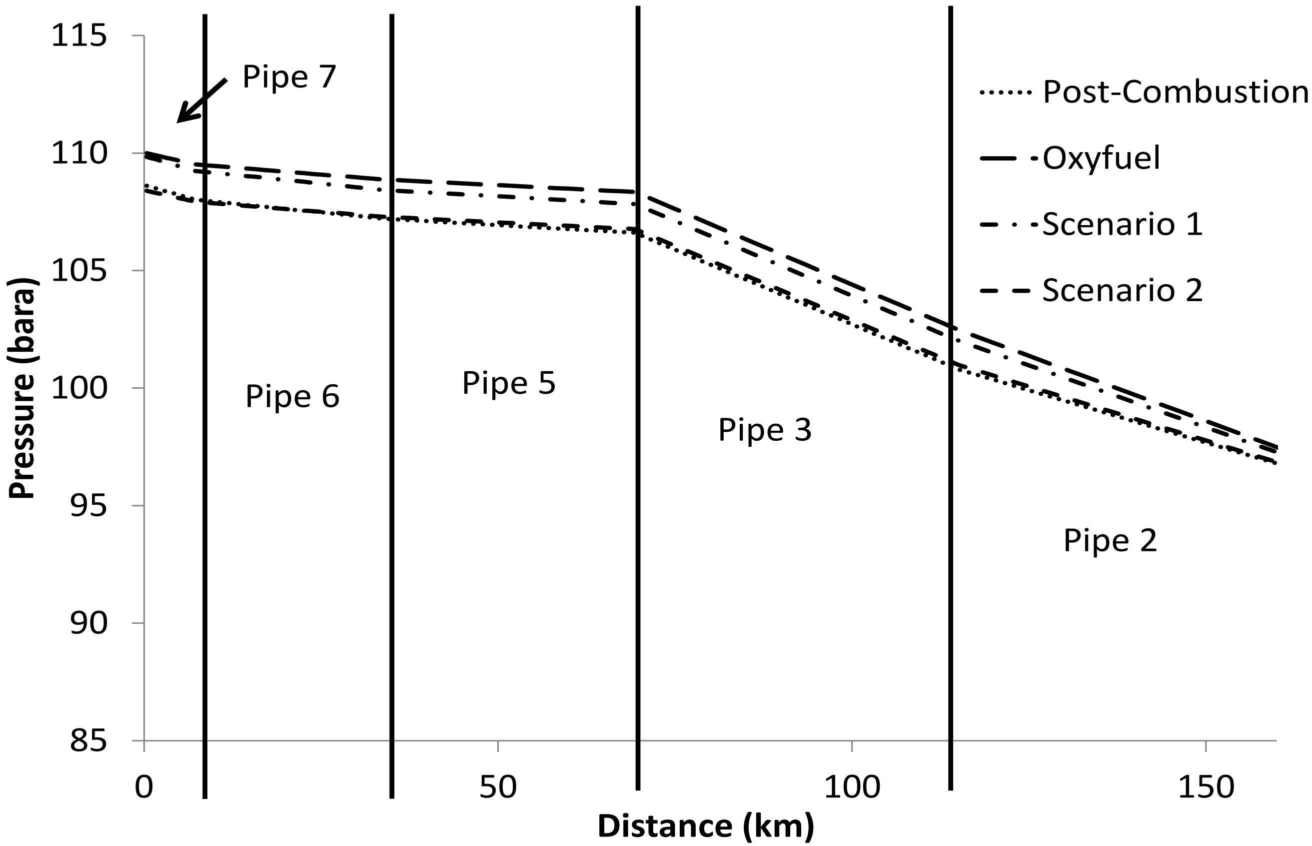
Pipeline networks – case studies

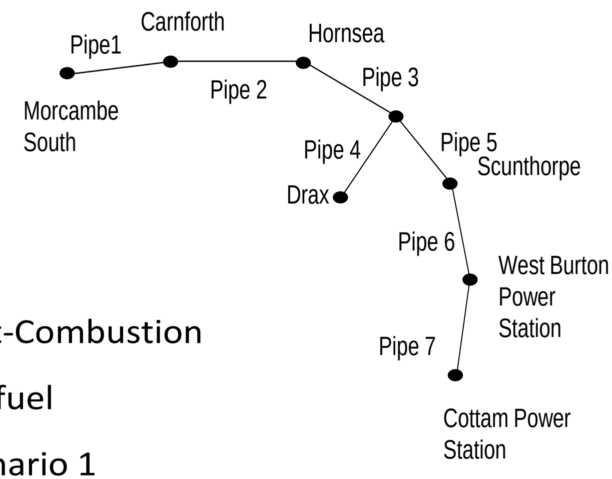
Feed flowrates and CO_2 stream compositions at sources

	Post-Combustion	Oxyfuel	Scenario 1	Scenario 2
Drax Flowrate (kg/s)	20.153	20.153	20.153	20.153
Drax Composition (vol/vol)	CO_2 – 0.998 N_2 – 0.002	CO_2 – 0.881 H_2O – 0.002 Ar – 0.057 N_2 – 0.037 O_2 – 0.023	CO_2 – 0.881 H_2O – 0.002 Ar – 0.057 N_2 – 0.037 O_2 – 0.023	CO_2 – 0.998 N_2 – 0.002
Cottam Flowrate (kg/s)	4.847	4.847	4.847	4.847
Cottam Composition (vol/vol)	CO_2 – 0.998 N_2 – 0.002	CO_2 – 0.881 H_2O – 0.002 Ar – 0.057 N_2 – 0.037 O_2 – 0.023	CO_2 – 0.998N_2 – 0.002	CO_2 – 0.881 H_2O – 0.002 Ar – 0.057 N_2 – 0.037 O_2 – 0.023

Pipeline networks – case studies

Variation of fluid pressure along main trunk line





Pipeline networks – case studies

Predicted feed pressures and CO_2 stream compositions at delivery points

	Post-Combustion	Oxyfuel	Scenario 1	Scenario 2
Drax Inlet Pressure (bara)	106.6	108.4	107.9	106.8
Cottam Inlet Pressure (bara)	108.6	110	109.8	108.4
Exit Composition (vol/vol)	CO_2 – 0.998 N_2 – 0.002	CO_2 – 0.881 H_2O – 0.002 Ar – 0.057 N_2 – 0.037 O_2 – 0.023	CO_2 – 0.904 H_2O – 0.002 Ar – 0.046 N_2 – 0.030 O_2 – 0.018	CO_2 – 0.976 H_2O – trace Ar – 0.011 N_2 – 0.009 O_2 – 0.004

The 10% drop in CO_2 purity at the inlets results in *ca* 2% rise of the inlet pressures

Publications

S. Brown, H. Mahgerefteh, S. Martynov, V. Sundara and N. Mac Dowell. **"A Multi-source Flow Model for CCS Pipeline Transportation Networks".** Submitted to *International Journal of Greenhouse Gas Control*

S. Martynov, N. Mac Dowell, S. Brown, and H. Mahgerefteh. **"Assessment of integral thermo-hydraulic models for pipeline transportation of dense-phase and supercritical CO2".** Submitted to *Industrial & Engineering Chemistry Research*

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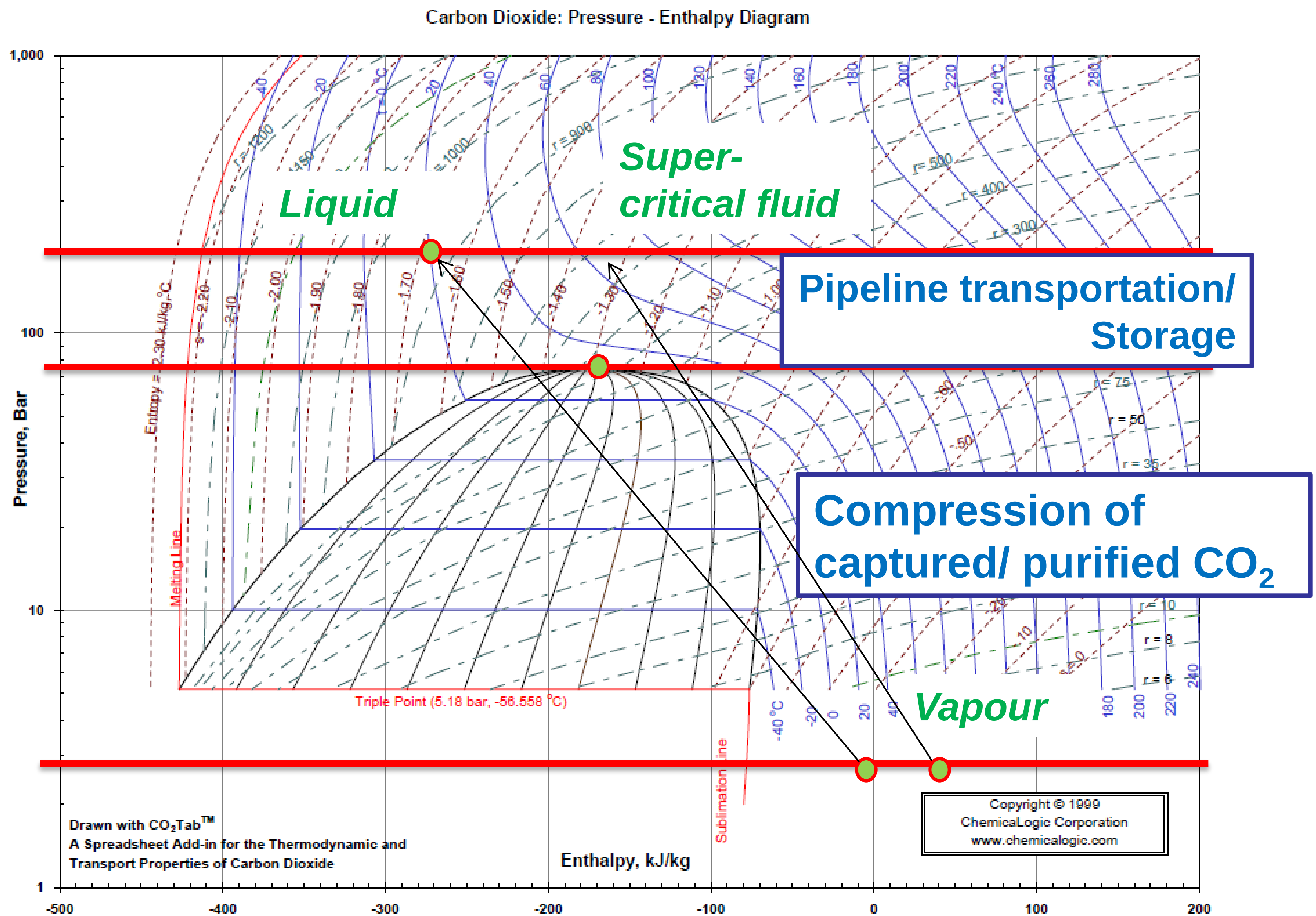
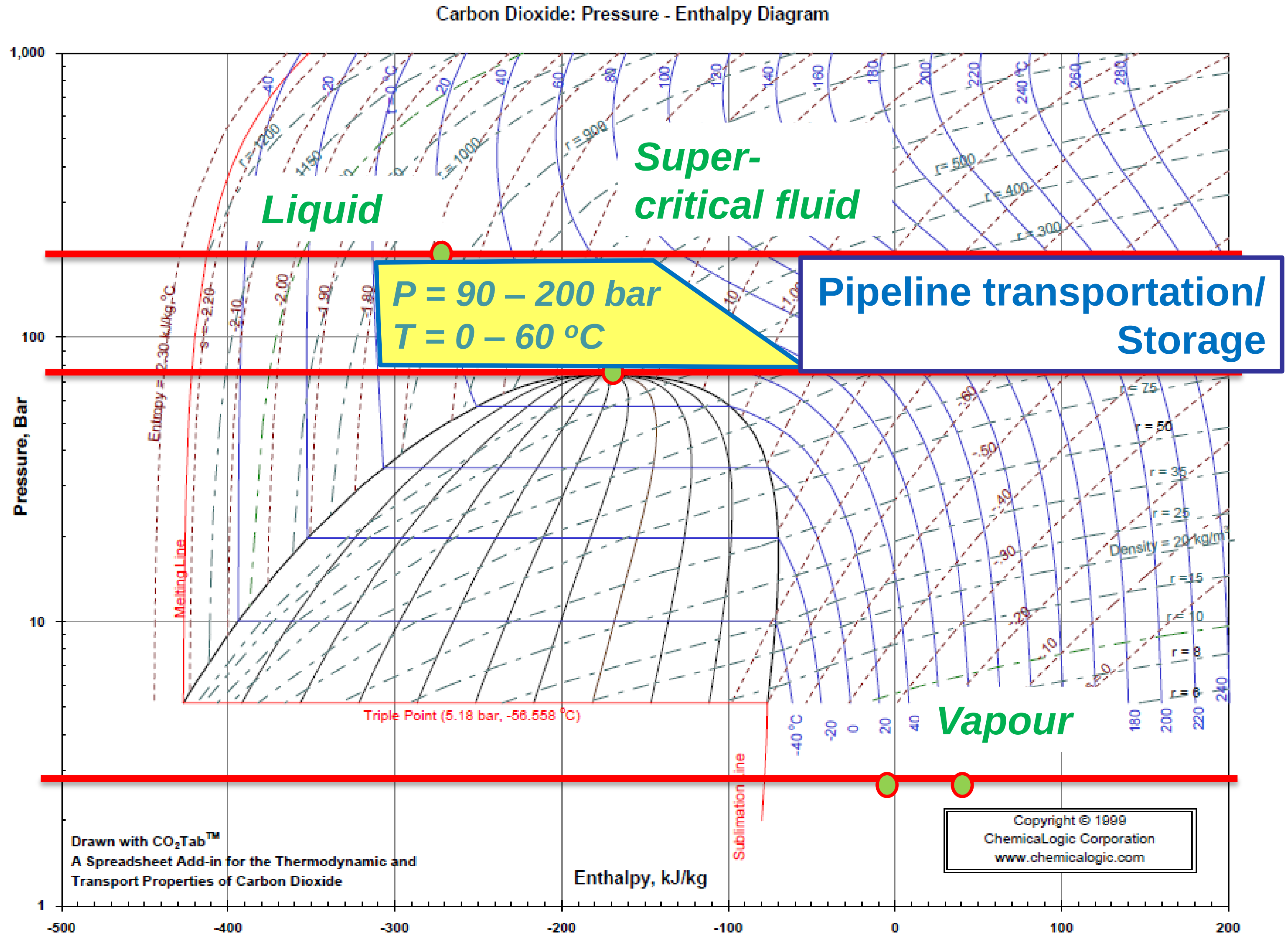
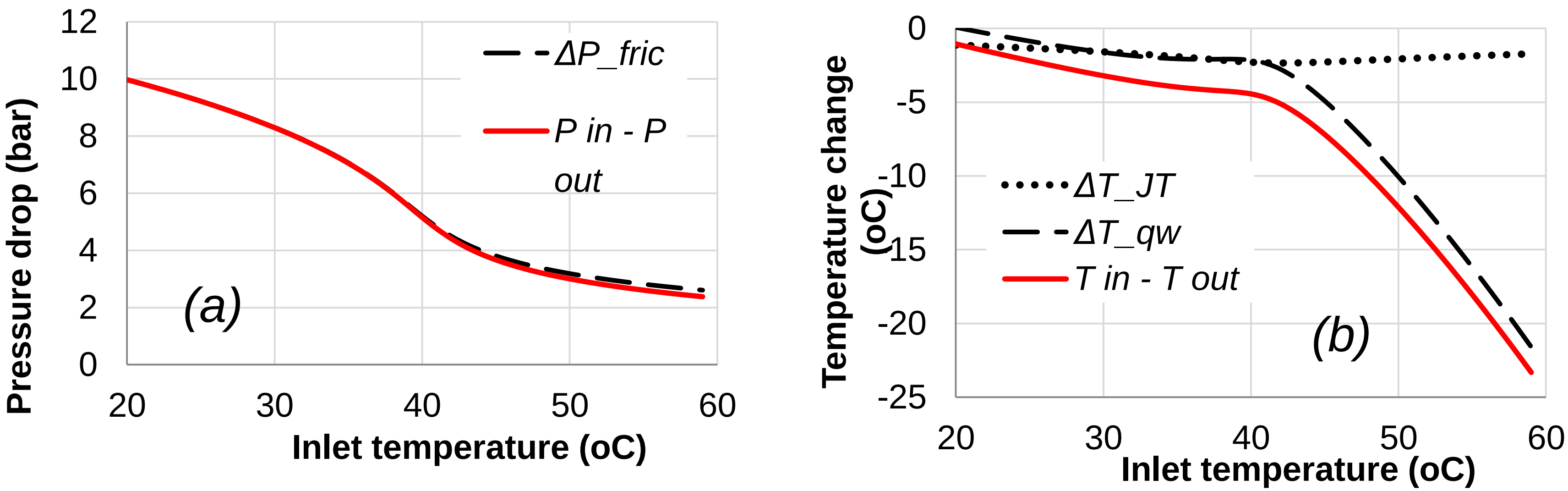
CO_2 pipeline transportation conditions



CO_2 pipeline transportation conditions



Pressure drop and temperature variation in a pipe

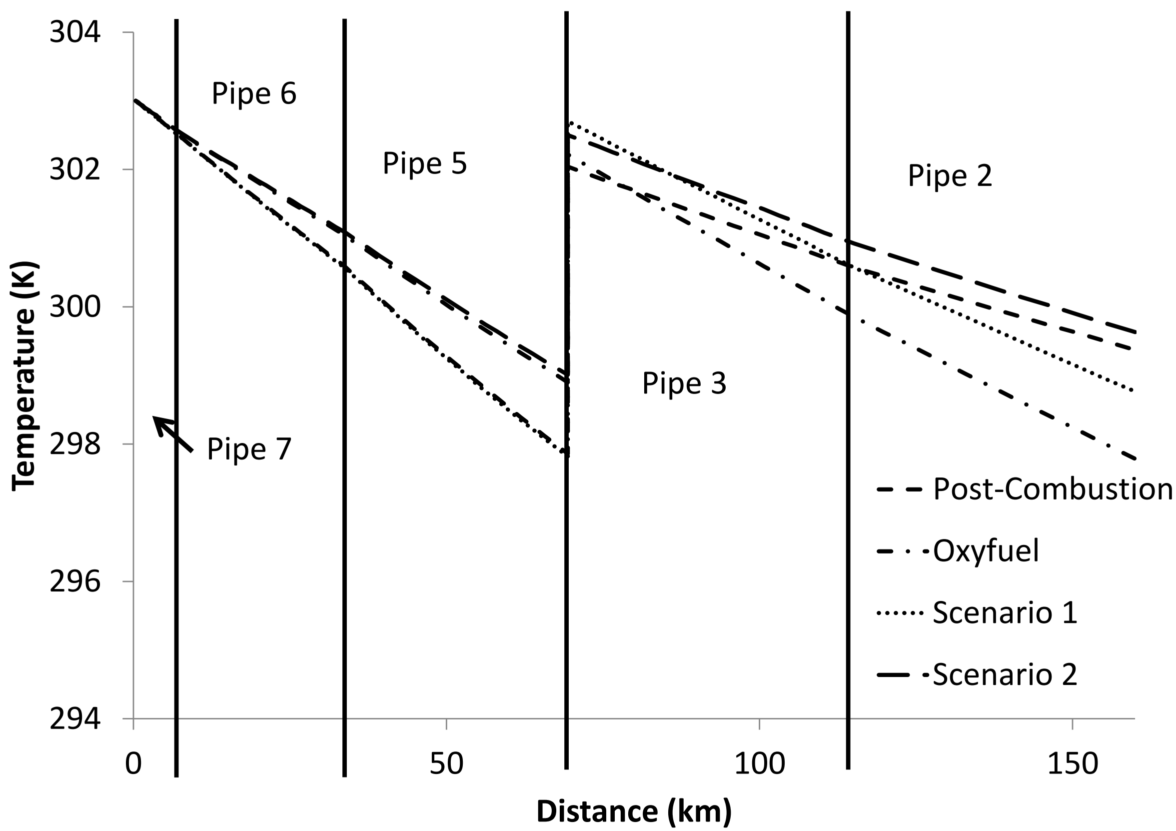


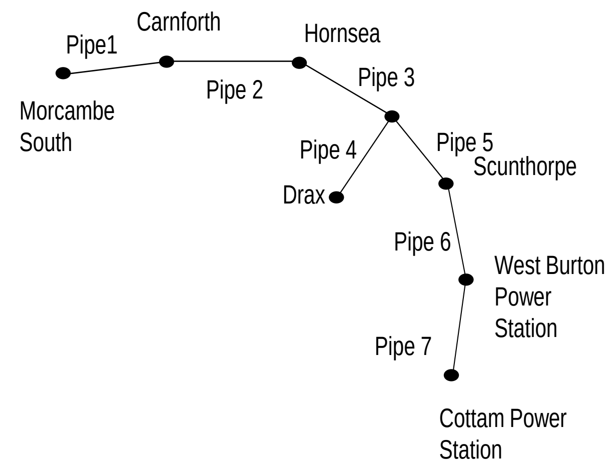
Predictions by Model 1A of the pipeline pressure drop, $p_{in} - p_{out}$, and its frictional component, Δp_f , *(a),* and the temperature change, $T_{in} - T_{out}$, and its components ΔT_{qw} and ΔT_{JT} *(b).*

Above-ground pipeline (T_a=20°C), D = 0.8 m, L = 20 km, p_{in}= 90 bar, u_{in} = 3 m/s.

Pipeline networks – case studies

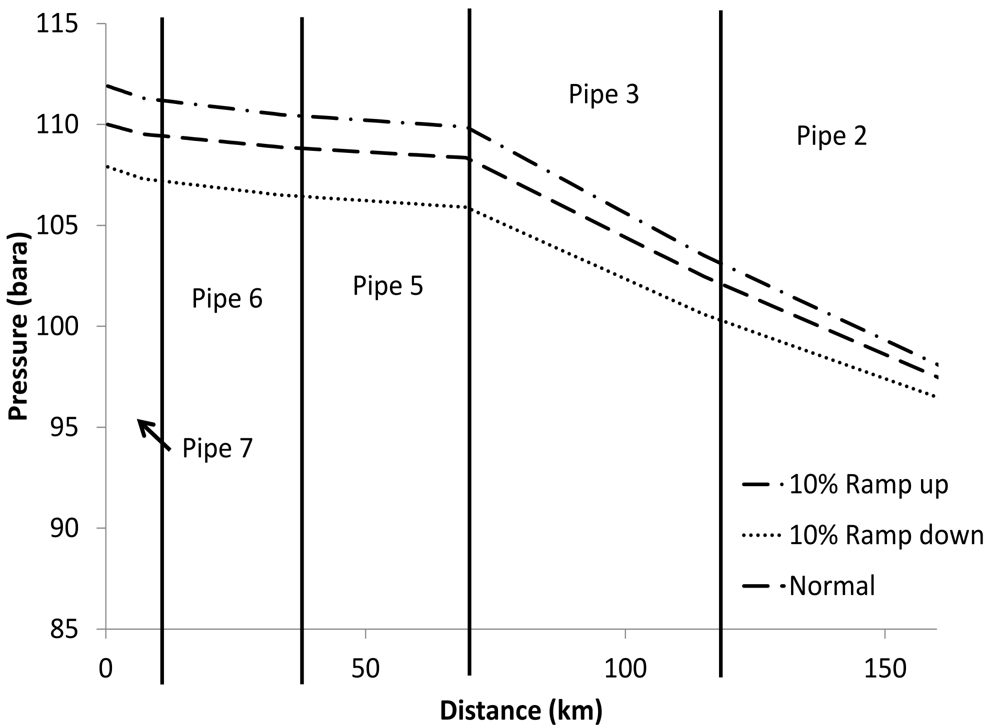
Variation of fluid temperature along main trunk line

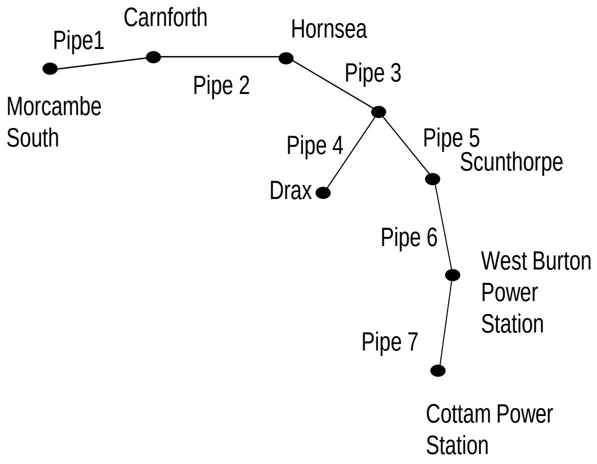




Pipeline networks – case studies

Variation of fluid pressure along main trunk line (Scenario 1)





	Scenario 1	Ramp-down	Ramp-up
Drax Inlet Pressure (bara)	107.9	105.9	109.9
Cottam Inlet Pressure (bara)	109.8	107.9	111.9
Exit Composition (vol/vol)	CO_2 – 0.904 H_2O – 0.002 Ar – 0.046 N_2 – 0.030 O_2 – 0.018	CO_2 – 0.906 H_2O – 0.002 Ar – 0.045 N_2 – 0.029 O_2 – 0.018	CO_2 – 0.902 H_2O – 0.002 Ar – 0.046 N_2 – 0.031 O_2 – 0.019