# Transient flow modelling of $CO_2$ injection into deep geological formations


Revelation Samuel

Supervised by

Prof. Haroun Mahgerefteh

Department of Chemical Engineering, University College London,

Torrington Place, London WC1E 7JE, United Kingdom


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# Background

- Geological sequestration of $CO_2$ has been recognised as an important strategy for reducing the $CO_2$ concentration in the atmosphere.

- From the head of the injection well to the reservoir the $CO_2$ is affected by several physical effects that contribute to the pressure and temperature profile along the well. Heat will be exchanged with the surrounding rocks along the well.

- Thus, this research is focused on developing economically viable techniques for geological sequestration of $CO_2$.

# Research objectives

This study is focussed on modelling the transient flow behaviour of carbon dioxide ($CO_2$) during geological sequestration. Our objectives are:

- ❖ Develop and validate a transient flow model for the injection of pure $CO_2$.
- ❖ Demonstrate the usefulness of the model developed by applying data from a real $CO_2$ injection system as a test case.
- ❖ Employ the findings to predict optimum $CO_2$ injection strategies.

# $CO_2$ injection challenges

**Injecting a highly-pressurised $CO_2$ into a formation with lower pressure will induce a rapid quasi-adiabatic Joule-Thompson expansion effect.**

**As such, the resulting effect on the formation may be:**

- ✓ **Blockage due hydrate and ice formation with interstitial water around the wellbore and**
- ✓ **Thermal shocking of the wellbore casing steel, leading to its fracture and ultimately escape of $CO_2$.**

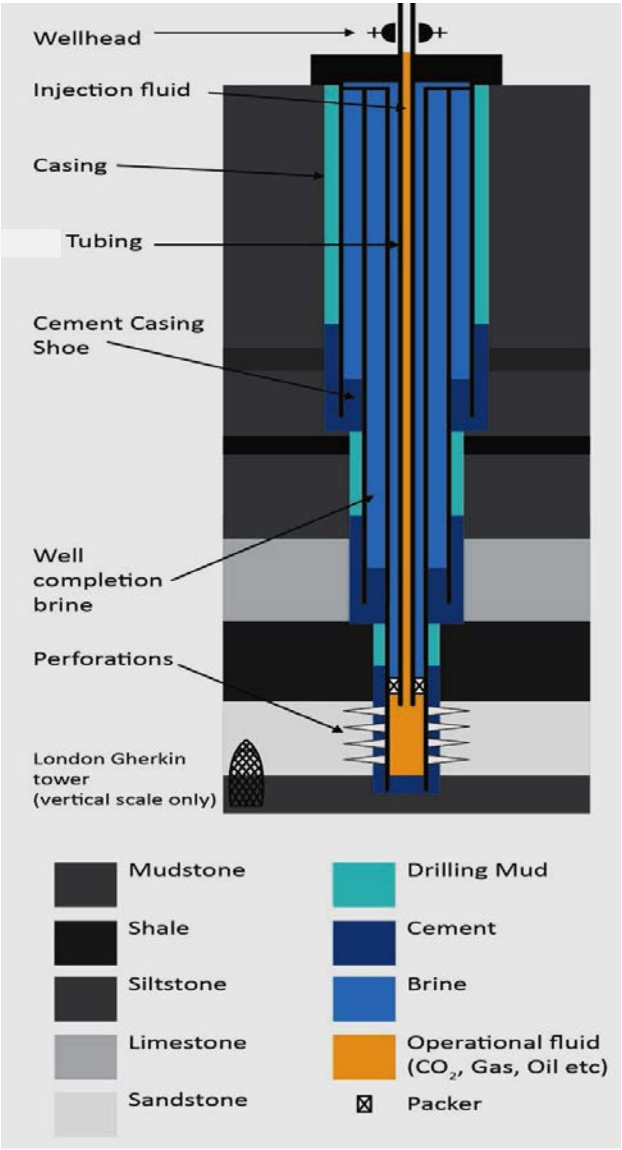



**Fig 1: $CO_2$ injection well (UKCCS, 2016)**

# Steps in model development

The development of a transient flow model for $CO_2$ geological sequestration comprises of three major steps:

- Formulating the basic governing (conservation) equations of the flow
- Selecting and implementing an efficient and accurate method that resolves or simplifies the model equations
- Validating the model against available field or experimental data.

# Model development

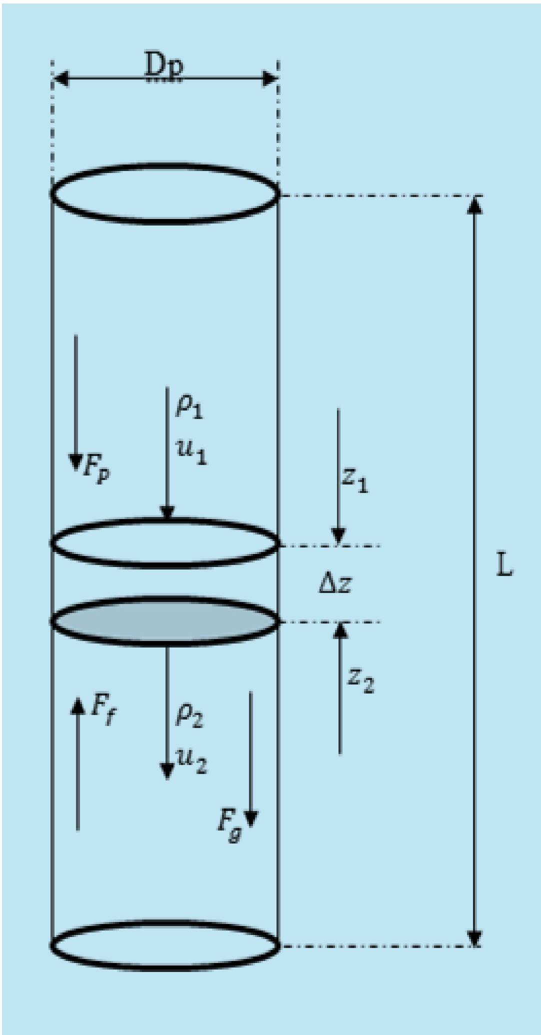



**Fig 2: Schematic $CO_2$ injection process diagram**

**The system of four partial differential equations for the $CO_2$ liquid/gas mixture, to be solved in the well tubing, can be written in conservative form as follows:**

$$\frac{\partial}{\partial t}U + \frac{\partial}{\partial z}F(U) = S_1 + S_2$$

**where**

$$U = \begin{pmatrix} \rho A \\ \rho u A \\ \rho E A \\ A \end{pmatrix}, \qquad F(U) = \begin{pmatrix} \rho u A \\ \rho u^2 A + AP \\ \rho u H A \\ 0 \end{pmatrix},$$

$$S_1 = \begin{pmatrix} 0 \\ P\frac{\partial A}{\partial z} \\ 0 \\ 0 \end{pmatrix}, \qquad S_2 = \begin{pmatrix} 0 \\ A(F + \rho\beta g) \\ A(Fu + \rho u\beta g + Q) \\ 0 \end{pmatrix}$$

**$A$ is the cross-sectional area,**
**$u$ and $\rho$ are the mixture velocity and density,**
**$P$ is the mixture pressure, while $E$ and $H$ represent the specific total energy and total enthalpy of the mixture, respectively. $z$ denotes the space coordinate, $t$ the time, $F$ the viscous friction force, $Q$ the heat flux, and $g$ the gravitational acceleration.**

# Initial and boundary conditions

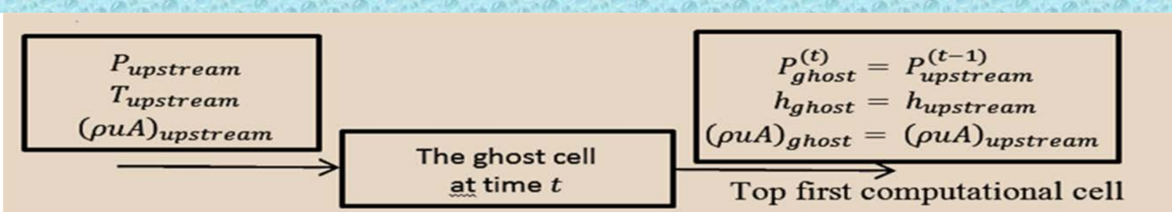
**The model was validated using Ketzin pilot site Brandenburg, Germany $CO_2$ injection well initial and boundary conditions (Moller et al, 2014).**

- Inlet pressure 57 bar, inlet temperatures are 10 °C and 20 °C, and injection mass flow rate 0.41 kg/s.
- Initial wellhead pressure 48 bar and temperature 10 °C,
- Total well depth 550m; 0.0889m internal diameter
- Initial bottom-hole pressure 68 bar and temperature 33 °C,

At the bottom of the well an empirical pressure-flow relationship derived from reservoir properties is employed:

$$\tilde{A} + \tilde{B} \times M + \tilde{C} \times M^2 = P_{BHF}^2 - P_{res}^2$$

At the top of the well, the pressure, enthalpy and mass flowrate in the ghost cell will equate those in the first computational cell at time, $t - \Delta t$.



# Numerical Solution Scheme

As the model equations cannot be solved analytically, a suitable numerical method has been employed within the Finite Volume framework proposed by Toro (2010):

- We first divide the domain in $N$ cells and integrate over the $i$-th computational cell $[z_{i-\frac{1}{2}}, z_{i+\frac{1}{2}}]$, $i = 1, \dots, N$, to yield the semi-discrete formulation:

$$\frac{d\boldsymbol{U}_i}{dt} = -\frac{1}{\Delta x}\left(\boldsymbol{F}_{i+\frac{1}{2}} - \boldsymbol{F}_{i-\frac{1}{2}}\right) + \boldsymbol{S}_{1,i} + \boldsymbol{S}_{2,i}$$

where $i + \frac{1}{2}$ denotes the interface between cells $i$ and $i + 1$, at which the inter-cell flux $\boldsymbol{F}_{i+\frac{1}{2}}$ has to be computed.

# Results

The flow and thermal behaviour of $CO_2$ in injection well is investigated using the above model and the corresponding results are plotted against experimental data. Firstly, looking at the variation in pressure with depth along the wellbore in Fig 4. The initial temperature profile in shown in Fig 5.

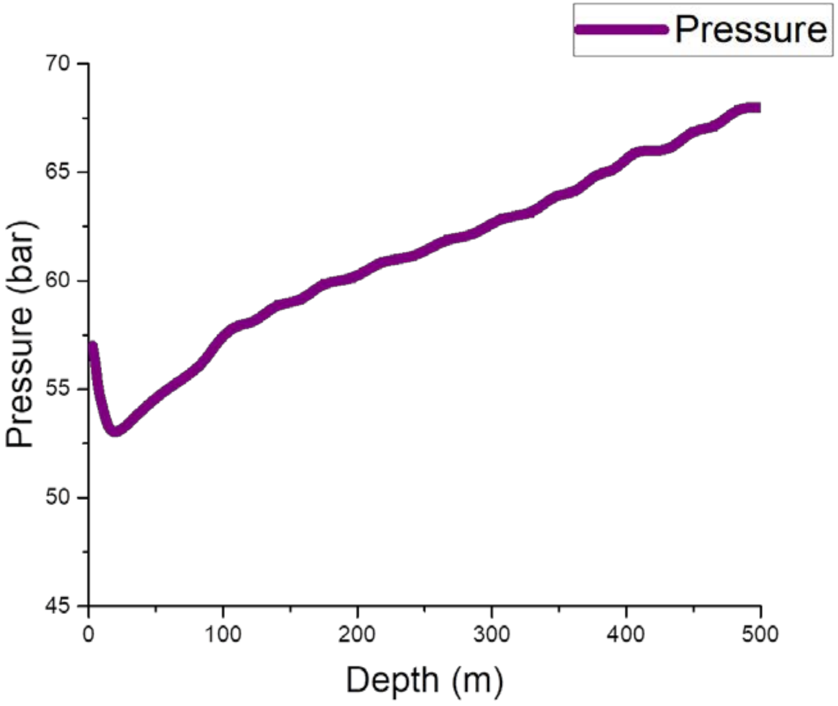



**Fig. 4: Variation in pressure with depth**

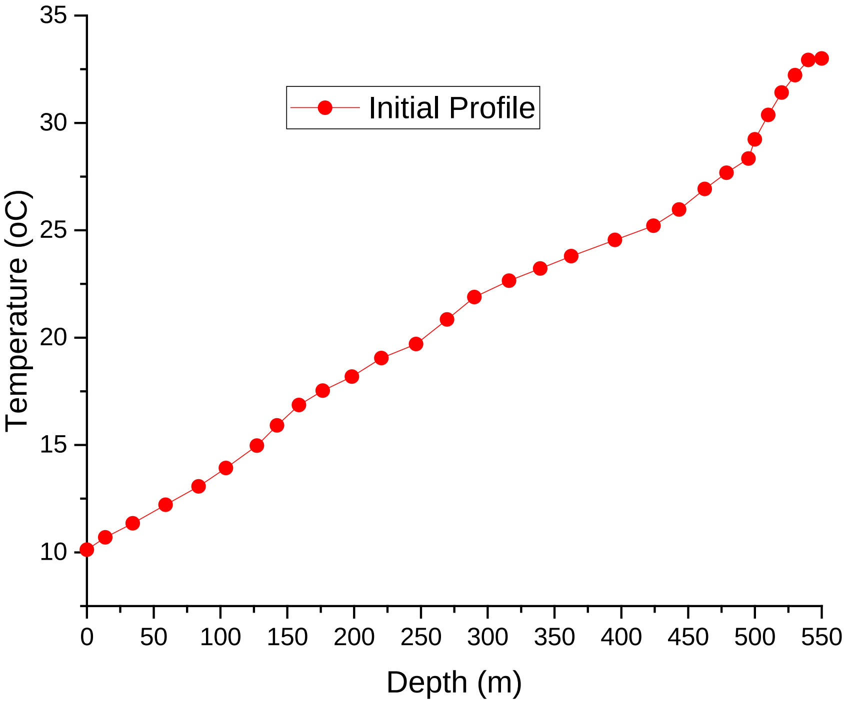



**Fig. 5: Initial well temperature profile**

# Results

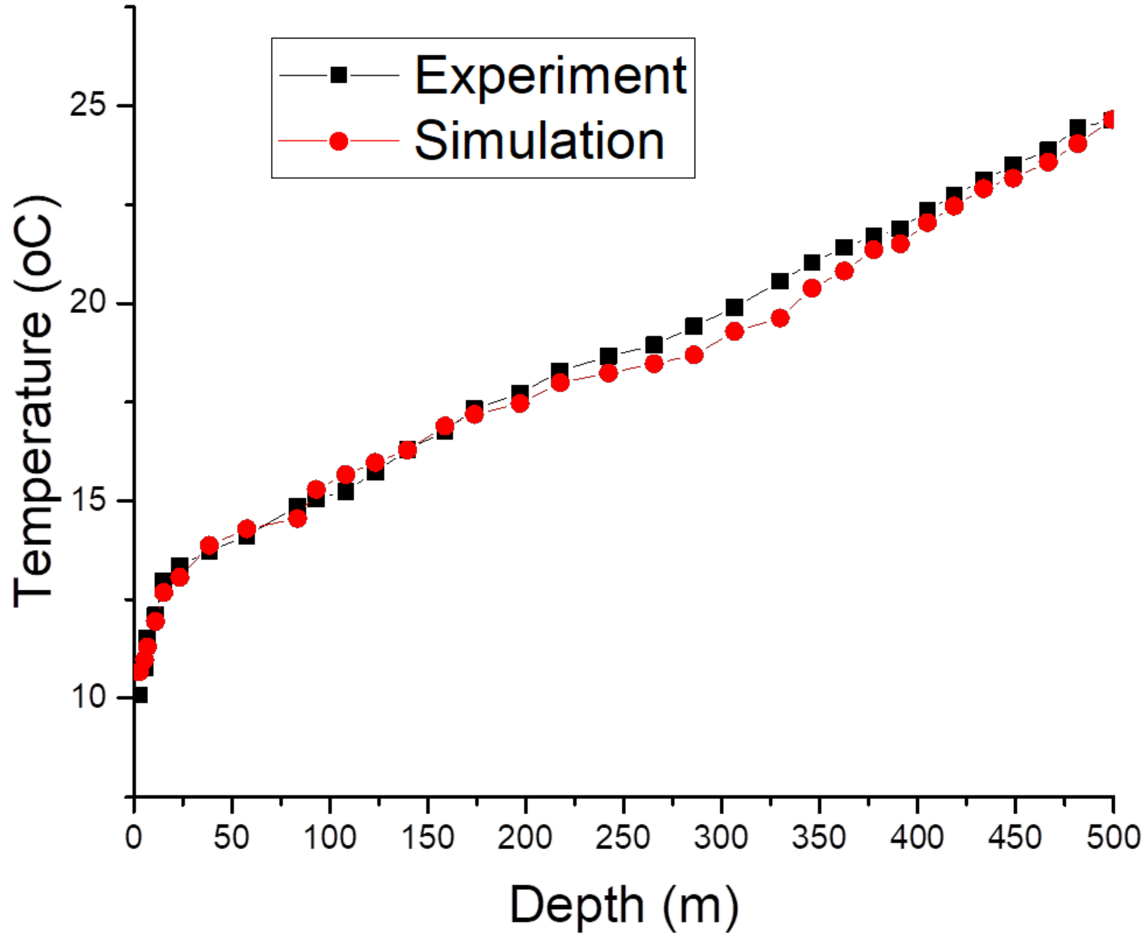



Fig. 6: Well temperature versus depth for 10°C inlet temperature

# Results

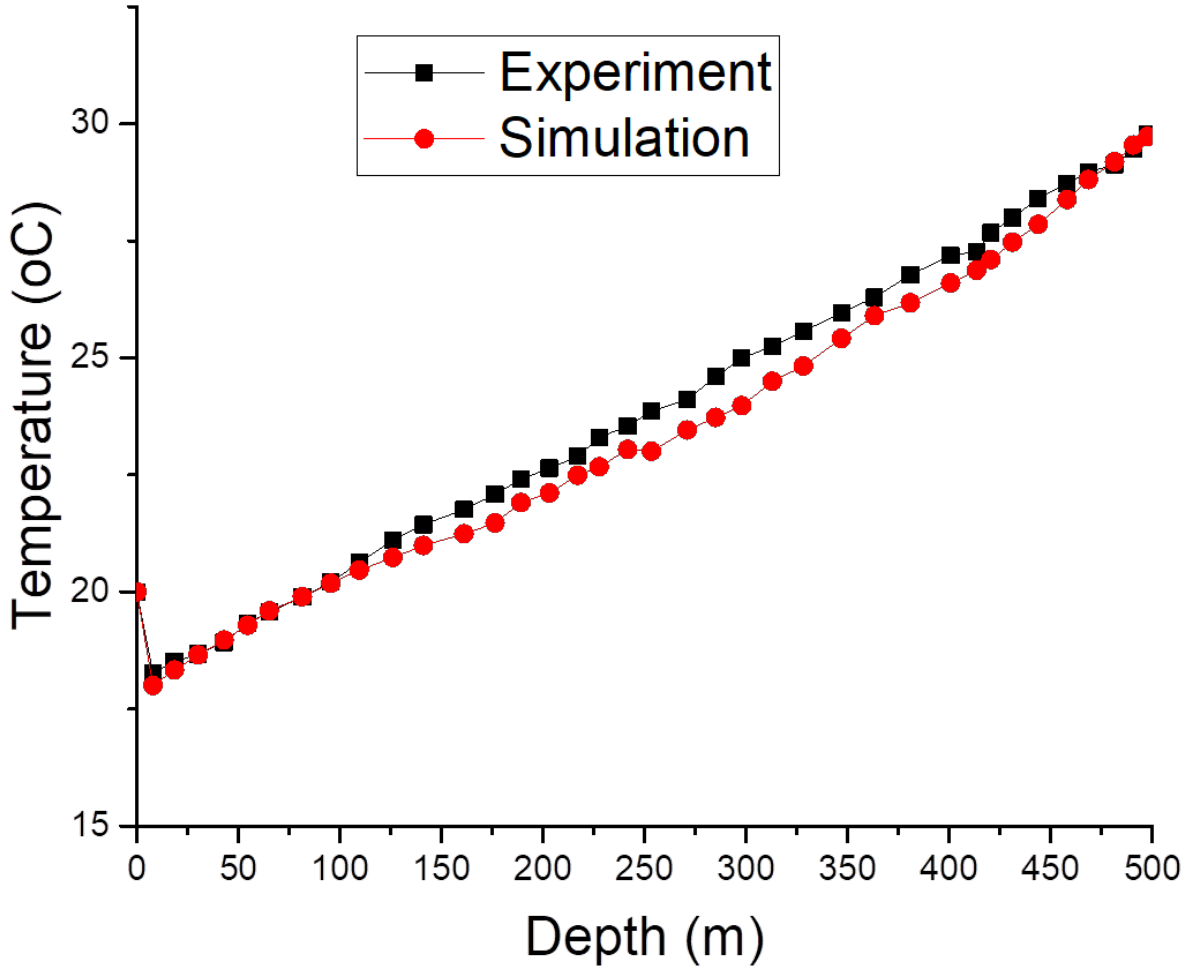



Fig. 7: Well temperature versus depth for 20°C inlet temperature

# Conclusion

- The simulation results for 10$^{o}$C and 20$^{o}$C injection inlet temperature condition showed good agreement with the experimental data.
- This shows the model is quite reliable and fairly accurate.

# Future works

Extent the model source terms to account for the injection of $CO_2$ stream with various impurities combination.

- Various $CO_2$ stream impurities compositions employed in previous models by Mahgerefteh *et al*, (2012) and Brown *et al*, (2013) in the fracture simulations according to post-combustion, pre-combustion, oxy-fuel and other capture technologies will be utilised.

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**ALL GLORY TO GOD ALMIGHTY**

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