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A Simplified 1-D Model for Calculating CO_2 Leakage through Conduits

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Problem Description

In geological CO_2 storage projects, a cap rock is generally needed to prevent CO_2 from leaking out of the storage formation. However, the injected CO_2 may still encounter some discrete flow paths such as a conductive well or fault (here referred to as conduits) through the cap rock allowing escape of CO_2 from the storage formation. As CO_2 migrates upward, it may migrate into the surrounding formations. The amount of mass that is lost to the formation is called attenuation. This report describes a simplified model to calculate the CO_2 mass flux at different locations of the conduit and the amount of attenuation to the surrounding formations.

Problem Setup

The problem setup is shown in Figure 1.

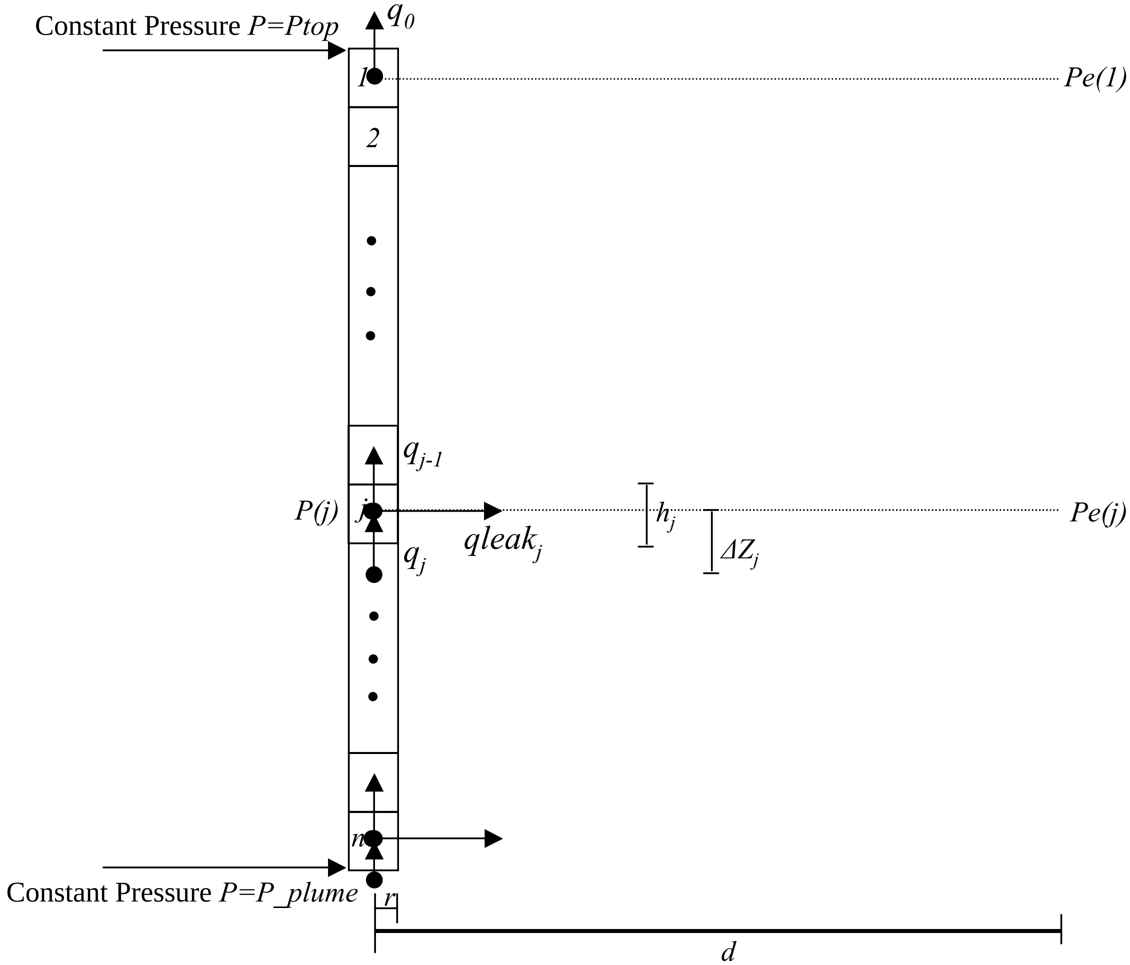

Figure 1. Problem setup

We consider single-phase flow of CO_2 neglecting initial brine displacement. The boundary conditions of the system are: constant pressure at the top (*Ptop*) which is set equal to hydrostatic pressure; constant pressure at the bottom (*P_plume*) set equal to hydrostatic pressure plus some overpressure due to CO_2 injection; and constant pressure at the far field set equal to hydrostatic pressure *Pe*. At steady state in this system,

$$q_j = q_{j-1} + qleak_j \tag{1}$$

where q_j is the mass flow rate (*kg/s*) between grid blocks j+1 and j, and $qleak_j$ is the leak-off mass flow rate (*kg/s*) from the jth grid block to the formation.

From Darcy's law, we can write the following equations:

$$q_j = \rho \frac{\kappa \pi r^2}{\mu} \frac{P_{j+1} - P_j}{\Delta z_j} \tag{2}$$

$$qleak_j = \rho \frac{2\pi k_j h_j}{\mu} \frac{P_j - P_e(j)}{\ln(d/r)} \tag{3}$$

where r is the radius of the conduit, d is the distance from the conduit to the far field where pressure is considered constant, ρ is the density of CO_2, μ is the viscosity of CO_2, k_j is the permeability of the formation adjacent to grid block *j,* and κ is the permeability of the conduits. P_j and $Pe(j)$ are the pressure and far-field pressure (hydro-static pressure), respectively, at grid block *j*, h_j is the thickness of grid block *j* and Δz_j is the distance between the center of grid blocks *j* and *j*+1.

These equations can be written for each grid block and combined with boundary conditions to calculate pressures and mass flow rates. A FORTRAN code was written to solve these equations. Below we will refer to this simplified model as the steady-state conduit model (SSCM).

Code Testing

An example problem is solved using three different approaches. Results are compared between the SSCM (described above), a TOUGH2 model of the same system at steady state, and the preliminary matlab code referred to as PMC (steady-state results).

The following properties are used for the test problem:

Water density (for establishing hydrostatic pressure): 998.057 kg/m^3
CO_2 density: 693.844 kg/m^3
CO_2 viscosity: 5.71336 e-5 Pa s

Conduit length: 140 m
Conduit radius r: 0.05 m
Distance d from the conduit to far field: 1102 m, so $ln(d/r) = 10$
Top pressure: atmospheric pressure ($Ptop = P_{atm}$).
Bottom pressure: hydrostatic pressure plus 5000 *Pa* overpressure (*P_plume*=*Pe*+5000 *Pa*)
Conduit permeability: 1.e-12 m^2

- Case 1

For this case, the surrounding formation has a permeability of 1.e-13m^2 at depth 130 – 140 m. The rest of the formation is impermeable. Discretization of the conduit at the depth of the permeable layer should be fine enough to capture the nonlinear pressure drops. To examine the discretization effect, runs with different grid-block size are also conducted. Results (mass flux in $kg{\cdot}m^{-2}\ s^{-1}$) are shown in Table 1. Comparisons of the three models are made for a grid size of 1 m. Additional comparisons are made between TOUGH2 and the SSCM for a grid size of 2 m, and between the SSCM and PMC for a grid size of 0.1 m.

Table 1. Comparison of mass flux ($kg{\cdot}m^{-2}\ s^{-1}$) at the top (z = 0 m), and bottom (z = 140 m) between the three models for different grid-block sizes for Case 1.

Number of gridblocks	Grid size (m)	CO_2 mass flux ($kg\ m^{-2}\ s^{-1}$)					
		SSCM top	SSCM bottom	TOUGH2 top	TOUGH2 bottom	PMC top	PMC bottom
14	10	0.03624	0.04836				

70	2	0.03624	0.09349	0.03636	0.09344		
140	1	0.03624	0.13540	0.03624	0.13514	0.03595	0.16189
280	0.5	0.03624	0.17647				
700	0.2	0.03624	0.20150				
1400	0.1	0.03624	0.20630			0.03620	0.20096

Results from these three models are very similar, especially between TOUGH2 and the SSCM. The mass flux along the conduit using the SSCM is shown in Figure 2.

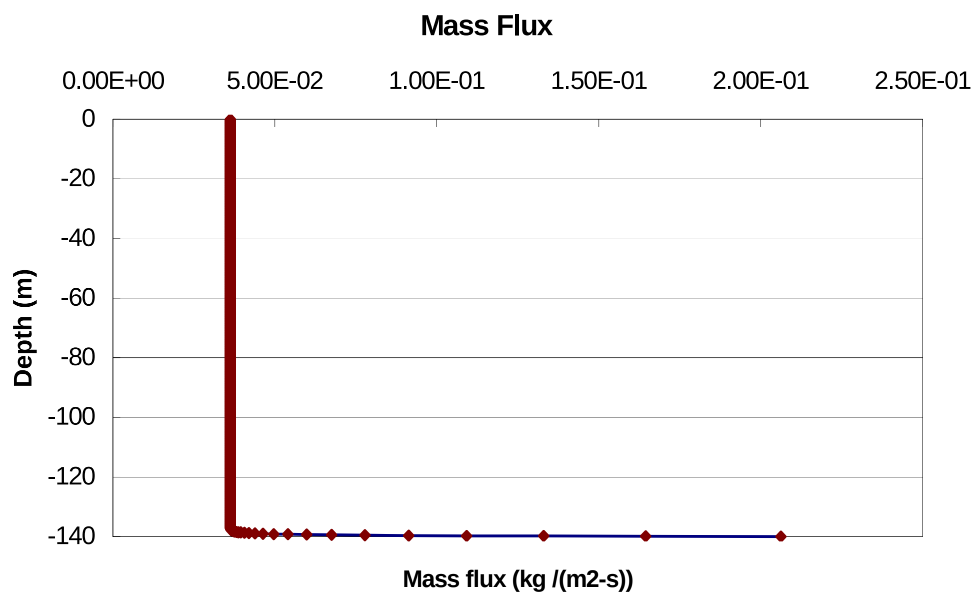

Figure 2. Mass flux along the conduit using the steady-state conduit model with a grid block size of 0.1 m for Case 1.

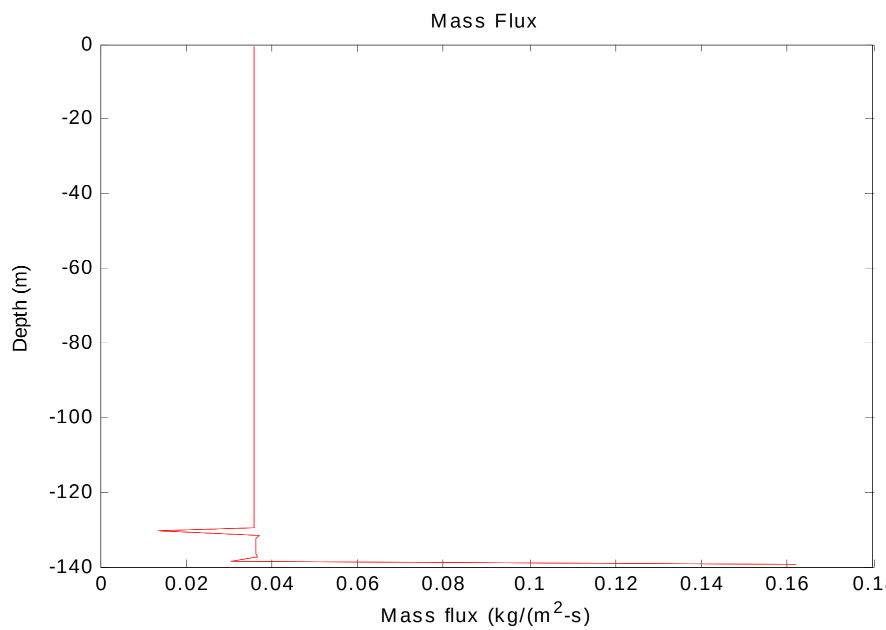

Figure 3. Mass flux along the conduit using the PMC model with a grid block size of 1 m for Case 1.

It seems that when the discretization is not fine enough, the PMC has some numerical issues (see Figure 3, mass flux for 1 m grid block size). However, this disappears when a finer discretization is used (0.1 m).

Results show most of the attenuation happens at the lower portion of the conductive formation. The upper portion of the conductive formation does not contribute much to the attenuation as has been pointed out previously (Minkoff, SIAM, Santa Fe, 2006). Therefore, a much finer discretization is needed for the conduits that sit at the lower part of the conductive formation.

- Case 2

The difference between Case 2 and the previous case (Case 1) is that the surrounding formation has a permeability of 1.e-15 m^2 at depth 130 – 140 m. Results are shown in Table 2.

Table 2. Comparison of mass flux ($kg \cdot m^{-2} s^{-1}$) at the top (z = 0 m), and bottom (z = 140 m) between the three models for different grid-block sizes for Case 2.

Number of gridblocks	Grid size (m)	CO_2 mass flux (kg m^{-2} s^{-1})					
		SSCM top	SSCM bottom	TOUGH2 top	TOUGH2 bottom	PMC top	PMC bottom
14	10	0.03633	0.04598				
70	2	0.03630	0.05265	0.03642	0.05254		
140	1	0.03630	0.05313	0.03629	0.05299	0.03592	0.06557
1400	0.1	0.03630	0.05330			0.03626	0.05470

In this case, a finer discretization is not as necessary as it is in Case 1 because of the much smaller attenuation due to the large contrast between the low formation permeability and high conduit permeability.

- Case 3

The difference between this case and Case 1 is that, in this case, the surrounding formation has a permeability of 1.e-13 m^2 located at depth 120 m – 130 m. Results are shown in Table 3.

Table 3. Comparison of mass flux ($kg \cdot m^{-2} s^{-1}$) at the top (z = 0 m), and bottom (z = 140 m) between the three models for different grid-block sizes for Case 3.

Number of gridblocks	Grid size (m)	CO_2 mass flux (kg m^{-2} s^{-1})					
		SSCM top	SSCM bottom	TOUGH2 top	TOUGH2 bottom	PMC top	PMC bottom
14	10	0.03624	0.04029				
70	2	0.03624	0.04173				
140	1	0.03624	0.04196	0.03624	0.04329	0.03593	0.05005
1400	0.1	0.03624	0.04211			0.03620	0.04271

Again, we see an overshoot in the PMC solution (Figure 4), even with a grid size 0.1 m. This is not observed in other models.

The discretization for this case is not very critical because more flux (caused by leak-off) leads to more pressure drop at the bottom layer, therefore the overpressure at the bottom of the leak-off layer is relatively smaller.

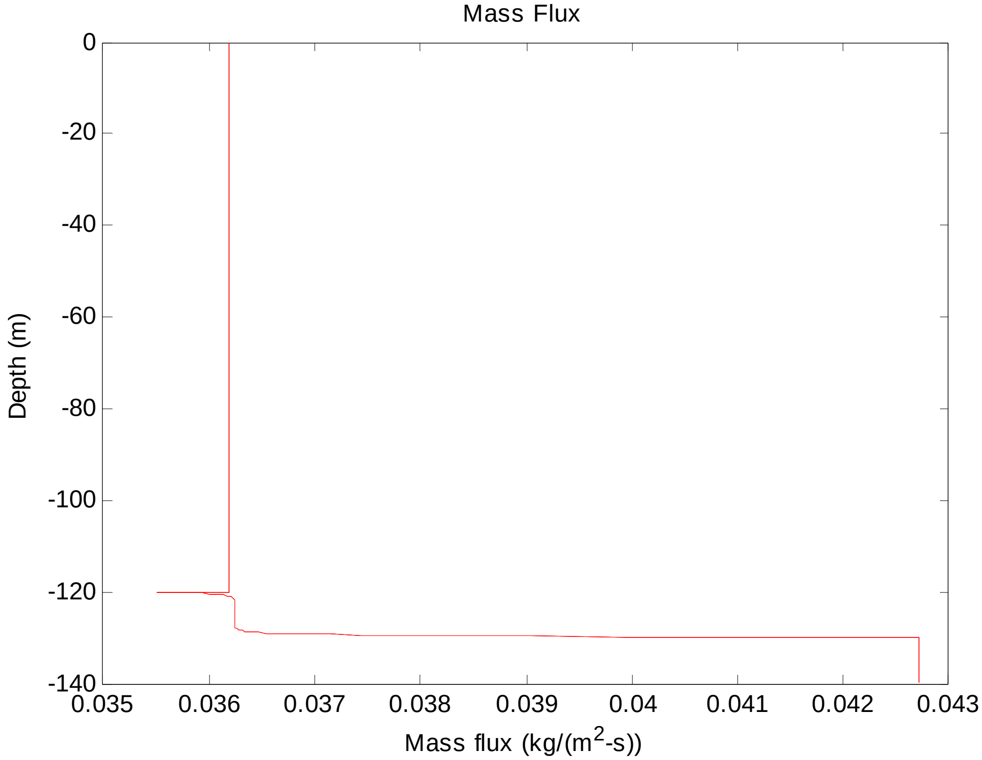

Figure 4. mass flux along the conduits using the PMC with a grid block size of 0.1 m for Case 3.

Conclusions

From the comparison among the three model results, we can conclude that the steady-state conduit model (SSCM) provides a more accurate solution than the PMC at a given discretization. When there is not a large difference between the permeability of the surrounding formation and the permeability of the conduits, and there is leak-off at the bottom formation (the formation immediately above the CO_2 plume), a fine discretization is needed for an accurate solution.

Based on this comparison, we propose to use the SSCM in the rapid prototype for now given it does not produce spurious oscillations, and is already in FORTRAN and therefore can be easily made into a dll for use in GoldSim.

Acknowledgments

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