Tracer Gas Diffusion in the Eagle Ford Shale, Austin Chalk, and Adjunct Vertical Formations in Southwestern Texas*

Qiming Wang1*, Qinhong Hu1, and Xiang Lin2

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1*Department of Earth and Environmental Science, The University of Texas at Arlington, Arlington, TX, United States (qiming.wang@mavs.uta.edu)
2School of Environmental Studies, China University of Geosciences, Wuhan, China

Abstract

As one of the two critical transport mechanisms in shale gas reservoirs, gas diffusion can be quantified by the diffusion coefficient (m²/s) within the shale matrix. To understand the diffusion behavior in rock matrices, 1-D short-duration (within 24 hours) tracer gas diffusion chamber tests at a room temperature were conducted on the major reservoirs (Eagle Ford B calcareous Shale and Austin Chalk), and adjunct vertical formations (Atoc Chalk, Buda Limestone, Eagle Ford A dolomitic ash bed, and Salmon Peak Limestone) in the Southernwestern Texas area. Associated with X-ray diffraction, thin section, and mercury intrusion porosimetry, the mineral composition, pore structure (both geometry and connectivity) were taken into the discussion of influencing factors. The results of gas diffusion tests show that the diffusion coefficients among these rocks with different lithologies vary in the magnitude of 10⁻⁸ to 10⁻⁷ m²/s and is influenced by pore structure especially pore connectivity.

References


Javadpour, F., 2016, Gas and liquid flow in shale. AAPG Geoscience Technology Workshop, Search and Discovery Article # 41780
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The University of Texas at Arlington

Boquillas (Eagle Ford) outcrop, Del Rio, TX
Outline

• Diffusion in natural rocks
• Sample properties
• Tracer gas diffusion method
• Summary

Eagle Ford B Calcareous Shale
Diffusion in natural rocks

Why diffusion is important?

• Occur at gas or liquid phase
• Rate-limiting or dominate process of fluid flow and mass transport in low-permeability geological media

Distinguishing features

• Random particle walk
• Driven by concentration gradient, influenced by temperature

(Javadvpour, 2015)
Applications

- Oil and gas recovery
- $\text{CO}_2$ sequestration
- Contaminant remediation
- Geologic disposal of radioactive waste

(GoldSim)
### Sample properties

<table>
<thead>
<tr>
<th>Series</th>
<th>Stage</th>
<th>Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Santonian</td>
<td>Austin Chalk</td>
</tr>
<tr>
<td></td>
<td>Coniacian</td>
<td>Atco Chalk</td>
</tr>
<tr>
<td>Upper Cretaceous</td>
<td>Turonian</td>
<td>Eagle Ford Fm. Boquillas Fm.</td>
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<tr>
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<td>Del Rio Formation</td>
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<tr>
<td></td>
<td>Cenomanian</td>
<td>Buda Limestone</td>
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<tr>
<td>Lower Cretaceous</td>
<td>Albian</td>
<td>Salmon Peak Limestone</td>
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</tbody>
</table>

**Outcrop in Midlothian, Ellis County, TX**

**Del Rio, Val Verde County, TX**
## Sample properties

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Mineral composition (wt.%)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Quartz</td>
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<tr>
<td>Austin Chalk</td>
<td>1.2</td>
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<tr>
<td>Atco Chalk</td>
<td>1.0</td>
</tr>
<tr>
<td>Eagle Ford B Calcareous Shale</td>
<td>15.5</td>
</tr>
<tr>
<td>Eagle Ford A Dolomitic Ash Bed</td>
<td>9.8</td>
</tr>
<tr>
<td>Buda Limestone</td>
<td>1.3</td>
</tr>
<tr>
<td>Salmon Peak Limestone</td>
<td>0.2</td>
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</table>

![Sample images](Atco Chalk Atco Chalk_Eagle Ford B Calcareous Shale Eagle Ford A Dolomitic Ash Bed Buda Limestone Salmon Peak Limestone)
Sample properties

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Pore Volume Distribution (%)</th>
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<tbody>
<tr>
<td>Austin Chalk</td>
<td>28.8%</td>
</tr>
<tr>
<td>Atco Chalk</td>
<td>7.73%</td>
</tr>
<tr>
<td>Eagle Ford B</td>
<td>2.05%</td>
</tr>
<tr>
<td>Eagle Ford A</td>
<td>15.4%</td>
</tr>
<tr>
<td>Buda Limestone</td>
<td>3.17%</td>
</tr>
<tr>
<td>Salmon Peak Limestone</td>
<td>7.63%</td>
</tr>
</tbody>
</table>

Pore-throat diameter (μm)
Tracer gas diffusion method

Currie method:
- First reported by Currie (1960).
- Commonly used in soil science
- Tracer gas: $O_2$

Advantages:
- Various sample shapes (irregulars; regulars: cylindrical, cubic, and granular)
- Applicable to various initial sample conditions (oven-dry, air-dry, partially saturated, fully saturated)
Tracer gas diffusion method

Diffusion coefficients analyzed in two directions perpendicular to each other.

Sample and holder was sealed by vacuum grease to minimize leakage.
Tracer gas diffusion method

Fick’s First law-based diffusion equation

\[ C_r = \frac{C_t - C_s}{C_0 - C_s} = \sum_{n=1}^{\infty} \frac{2h \exp\left(-\frac{D_p \alpha_n^2 t}{\phi}\right)}{L(\alpha_n^2 + h^2) + h} \]

(Rolston and Moldrup, 2002)

At ln-ln scale,

\[ \ln C_r = -\frac{D_p \alpha_1^2 t}{\phi} \ln \left(\frac{2h}{L(\alpha_1^2 + h^2) + h}\right) \]

\( \ln C_r \) is a linear function to \( t \) with a slope of \( \frac{-D_p \alpha_1^2}{\phi} \)

Diffusion coefficient \( D_p \) could be determined when \( \alpha \) and \( \phi \) is known.

- \( C_r \): tracer gas concentration
- \( C_t \): tracer gas concentration in the chamber when \( t=t \)
- \( C_0 \): tracer gas concentration in the chamber when \( t=0 \)
- \( C_s \): tracer gas (\( O_2 \)) concentration in atmosphere
- \( h=\phi/a \)
- \( A \): the length or volume of the diffusion chamber or volume of chamber per area of the sample
- \( D_p \): diffusion coefficient of sample to tracer gas
- \( \alpha_n \): the positive roots of \( \alpha_n \tan(\alpha_n L)=h \), with \( n=1,2,\ldots \). When \( t >0 \), the terms for \( n \geq 2 \) are negligible due to the very small influence on the result when compared to \( n=1 \)
Tracer gas diffusion method

Austin Chalk $\Phi=28.8\%$  Dominant pore diameter: 0.1-1 µm
Tracer gas diffusion method

Eagle Ford B Calcareous Shale $\Phi=2.05\%$

![Graph showing diffusion curves for Eagle Ford X and Y](image-url)

- Eagle Ford X: $D_p = 1.358 \times 10^{-7} \text{ m}^2/\text{s}$
- Eagle Ford Y: $D_p = 2.020 \times 10^{-7} \text{ m}^2/\text{s}$
The results show directional heterogeneity.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Direction X</th>
<th>Direction Y</th>
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</thead>
<tbody>
<tr>
<td>Austin Chalk</td>
<td>4.952E-07</td>
<td>5.147E-07</td>
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<td>Atco Chalk</td>
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<td>3.427E-08</td>
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<td>Eagle Ford A</td>
<td>2.417E-07</td>
<td>3.110E-07</td>
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<tr>
<td>Dolromatic Ash Bed</td>
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<tr>
<td>Eagle Ford B</td>
<td>1.345E-07</td>
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<tr>
<td>Calcareous Shale</td>
<td>1.345E-07</td>
<td>2.020E-07</td>
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<tr>
<td>Buda Limestone</td>
<td>1.217E-07</td>
<td>3.012E-07</td>
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<tr>
<td>Salmon Peak Limestone</td>
<td>1.968E-07</td>
<td>1.137E-07</td>
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</table>

**Tracer gas diffusion method**

![Graph showing directional heterogeneity](image-url)
At ln-ln scale,

\[ \ln C_r = -\frac{D_p \alpha_1^2 t}{\phi} \ln \left( \frac{2h}{L(\alpha_1^2 + h^2) + h} \right) \]

What is the porosity used in the $D_p$ calculation?

- For monolithic samples: with different pore connectivity
- For granular samples: with inter- and intra-granular pore space

Issues in determining $D_p$

Pores are not 100% interconnected in rock matrix

- Porosity $\phi$ used is the porosity of the whole monolithic rock
- Porosity $\phi$ should be using is the fluid flow porosity in a specific direction
Pore connectivity

- Well connected materials: soils, granular rock samples, loose sandstone, and porous carbonate rocks
- Poorly connected materials: tight sandstone, tight carbonate rocks, crystalline rocks, shales, and evaporites

\[
\ln C_r = - \frac{D_p \alpha_1^2 t}{\phi} \ln \left( \frac{2h}{L(\alpha_1^2 + h^2) + h} \right)
\]

Well connected:

\[
\phi_{\text{fluid flow}} \approx \phi_{\text{whole sample}}
\]

\[
D_p (\text{true}) \approx D_p (\text{calculated})
\]

Poorly connected:

\[
\phi_{\text{fluid flow}} < \phi_{\text{whole sample}}
\]

\[
D_p (\text{true}) < D_p (\text{calculated})
\]
Tracer gas diffusion method to determine the diffusion coefficient is applicable to a wide range of rock lithologies, as demonstrated in a vertical profile in Texas.

Porous Austin Chalk has a porosity of 28.8% and average diffusion coefficient of $5.050 \times 10^{-7}$ m$^2$/s.

Tight Eagle Ford B Calcareous Shale has a porosity of 2.05% and average diffusion coefficient of $1.683 \times 10^{-7}$ m$^2$/s.

Diffusion coefficient will be overestimated if an incorrect porosity, which is related to pore connectivity, is used in the calculation.
Acknowledgements

Qiming Wang
Ph.D. student
UT Arlington
Email: qiming.wang@mavs.uta.edu

Dr. Qinhong (Max) Hu
Professor
UT Arlington
Email: maxhu@uta.edu

Xiang Lin
Ph.D. student
China University of Geoscience (Wuhan)
Email: xlin6117@foxmail.com

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