Marangoni Effect Maintains Fast Evaporation in Near-Fracture Porous Media

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Background

- Fracture flux $\perp$ matrix-fracture interaction
- Fracture flux that is convection dominated
- Strong mass transport between fracture and porous matrix
1. The Marangoni effect often occurs along an interface between two fluids due to a gradient of the surface tension. This surface tension gradient could generate when there is a temperature gradient caused by evaporation.

2. The isothermal evaporation has been researched extensively. However, when the evaporation is drastic, the temperature at drying front can be much lower than other regions in the porous media and thus resulting in significant temperature gradient.

3. Such drastic drying in porous media occurs very commonly in CO2 sequestration, gas condensate reservoir and shale gas recovery, water management in fuel cell, etc, where extensive phase changes take place at near-fracture zone.
Results and Observations

Slow evaporation: layer-by-layer and sublinear

- Micromodel I, pentane
- Gas injection with mild evaporation
- Dry fracture surface formed
- Become diffusive after $S > 0.2$

Low gas injection rate (0.02 ml/min; 1.2X10^-4 kg/m^2/s)
Gas (blue) Saturation = 30%

Movie (X20)
Results and Observations

Slow evaporation: layer-by-layer and sublinear

- Micromodel II, isoheptane (even slower)

Low gas injection rate (0.02ml/min; 1.2X10^-4 kg/m²/s)
Gas invasion order (colored)

Turning Point: S=0.25

Movie (X1000)
Results and Observations

Strong evaporation: constant evaporation rate

- Micromodel I, pentane
- Gas injection with extensive evaporation
- Liquid at fracture surface maintained
- Constant evaporation rate keeps until $S > 0.5$

High gas injection rate (100ml/min; 0.7 kg/m²/s)
Gas (blue) Saturation = 30%

Movie (X20)
Results and Observations

Strong evaporation: constant evaporation rate

- Micromodel II, pentane

High gas injection rate (100ml/min; 0.7X10^-4 kg/m^2/s)
Gas invasion order (colored)

S=0.42

Movie (X60)
Results and Observations

Temperature decrease only at the entrance

Temperature decrease at the whole top fracture
Discussions

Quasi-static V.S. Extensive evaporation

- Low temperature gradient
- Layer-by-Layer evaporation
- Mass transfer distance gradually increase

- High temperature gradient
- Liquid bridge maintained
- Unchanged mass transfer
Let the heat transfer characteristic time as \( t_{hf} \), evaporation characteristic time as \( t_{ev} \)

We then have

\[
\begin{align*}
    t_{hf} &= \frac{L^2}{\phi \alpha} \\
    t_{ev} &= \frac{V_{\phi}}{\dot{m}}
\end{align*}
\]

- \( L \) - characteristic length;
- \( \phi \) - porosity;
- \( V_{\phi} \) - pore volume, \( cm^3 \);
- \( \dot{m} \) - critical evaporation rate of pentane, ml/min;
- \( \alpha \) – thermal diffusion coefficient of pentane, \( 8.22 \times 10^{-8} m^2/s \) at room temperature;

When \( t_{hf} < t_{ev} \), there is no Marangoni effect;
When \( t_{hf} > t_{ev} \), the Marangoni effect emerges.
We also have:
P_{air} - Atmosphere pressure, 100 kPa;
P_{pentane,liquid} - Saturated vapor pressure of pentane, 70.83 kPa;
\rho_l - Liquid density of pentane, 620.78 kg/m^3;
\rho_g - Vapor density of pentane, 2.05 kg/m^3;
v_{pentane,vapor} - Pentane vapor velocity, ml/min;
v_{injection} - Air injection velocity, ml/min;

When \( v_{pentane,vapor} = \frac{\rho_l}{\rho_g} \dot{m}_c = 2.81 \text{ml/min} \)

Thus, the air injection velocity should be

\[ v_{injection} = \frac{P_{air} v_{pentane,vapor}}{P_{pentane,liquid}} - v_{pentane,vapor} \]

\[ \approx 1.16 \text{ml/min} \]

When air injection rate \( q > 1.16 \text{ml/min} \), Marangoni effect would emerge and become more severe as the increase of air injection rate.
1. Experimental results are given to prove that other than isothermal condition, Marangoni effect could reshape the drying pattern and maintains fast evaporation when the fracture flow is drastic at the drying front. Infrared camera shows there generates a significant non-uniform temperature gradient through the porous media.

2. At low (0.02ml/min) air injection rate, the main drying front moves in a classic capillary fingering pattern, the evaporation dynamics is corresponded and balanced with the injection flow rates, as both the viscous dissipation and Marangoni effect are negligible.

3. At high (100ml/min) air injection rate, we observe the strong cool belt around the surface, which induces strong Marangoni effect as the gas fingers move inward to deep porous medium with different preferential paths while maintaining the liquid bridge for keeping the drying front at the entrance.

4. We calculate for our micromodel condition the Marangoni effect may emerge when the air injection rate is higher than 1.16ml/min and would become more severe as the injection rate increases.
Thanks for your time

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