Velocity Measurement in Porous Media Using Steady-State Free Precession

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Introduction: Velocity measurements in porous media have important applications in petroleum systems, perfusion in biological tissues, drug delivery, and nutrient transport in plants. Pulsed field gradient techniques are commonly used for velocity measurements [1]. Steady-State Free Precession (SSFP) produces a periodic magnetization pattern [2] that is sensitive to flow [3]. This flow sensitivity, first reported in 1986 [4], arises from the distortion of the magnetization pattern under steady flow, leading to the formation of a new steady state [5].

Methods: This distortion was modeled using the Bloch-Torrey equations. We solved these equations analytically using Fourier series decomposition to predict the alteration of the steady-state response under steady flow conditions. To validate the model, steady brine flow was established through a Bentheimer sandstone core plug using a high-precision Pharmacia pump.

Results and discussion: As demonstrated both theoretically and experimentally in this study, SSFP measurements under steady flow conditions produce a periodic steady-state magnetization that exhibits strong flow sensitivity. This sensitivity manifests as signal attenuation in the longitudinal magnetization and as a systematic phase shift in the transverse magnetization, as shown in Fig. 1. The steady-state longitudinal magnetization and the phase of the transverse magnetization were simultaneously fit to the analytical solution, enabling quantitative velocity measurement.

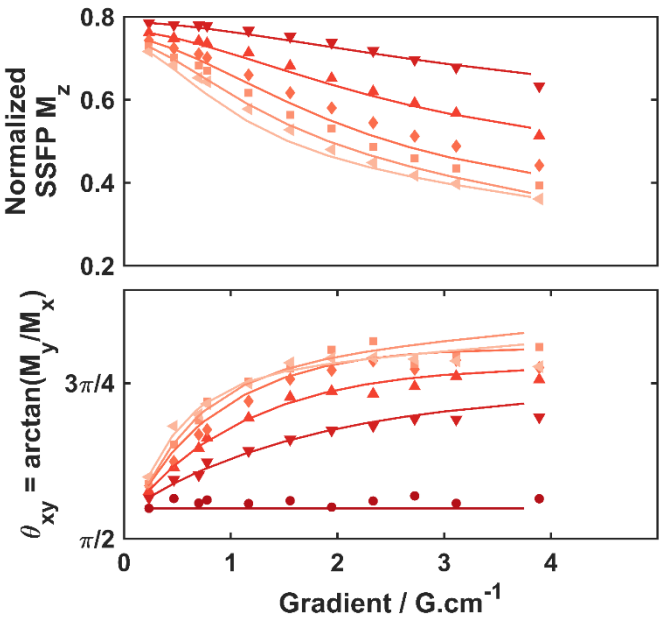

Fig. 1: (a) Measured steady-state longitudinal magnetization normalized to the no-flow case, and (b) phase of the transverse magnetization at the steady-state versus gradient in the direction of mean pore velocity of 0 (●), 105 (▼), 210 (▲), 315 (♦), 420 (■), and 526 (◀) µm/s in a Bentheimer sandstone. Solid lines are the result of the analytical solution fitting the experimental data.

Conclusions: The SSFP technique was employed to obtain quantitative velocity measurements in porous media. This method has been adapted for imaging using a preparation-readout strategy. In addition to local velocity measurement, this method offers valuable insights into fluid dynamics within porous structures.

References:
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