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Interpreting Pore-Scale Fluctuations: Predicting Transport Coefficients in Multiphase Flow through Porous Media Using the Green Kubo Formulation - An Experimental Investigation

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Pore scale fluctuations during multiphase flow in porous media have been observed over the past decade particularly at capillary dominated flow regimes. While multiphase flow in porous media is typically predicted using models that employ average properties, the current models do not incorporate these fluctuations at the pore scale. It therefore remains unclear how flow fluctuations can be integrated into existing models and to what degree they are related to energy dissipation.
Herein, we study pore scale fluctuations during steady state multiphase flow using the concept of non-equilibrium thermodynamic and statistical mechanics. We investigate, for the first time, how the Green Kubo formulation of the fluctuation dissipation theorem (FDT) can be used to predict the transport coefficient from the two-phase extension of Darcy's law. Flowrate-time series data are recorded at the millisecond time scale using a novel experimental setup that allows for the determination of flow fluctuation statistics. Steady state coreflooding experiments were conducted using DI water and decane as the wetting and non-wetting phase. A water fractional flow of ~0.5 was used while varying the total capillary number, Ca. By using Green Kubo relations, a transport coefficient is predicted based on the integrated autocorrelation function (ACF). The transport coefficient using conventional Darcy's linear law was also compared with the FDT approach.
Notable fluctuations were observed at all Ca studied. A linear relationship between average flux and pressure drops was observed at the lowest Ca. Hence, obeying Darcy's law. At higher Ca but still within capillary dominated flow regime, there was a systematic deviation from the linear trend. Thus, a non-Darcy behaviour was observed. Statistical frequency analysis of the flow fluctuations further shows non-Gaussian feature, that is more pronounced at the lowest Ca. By using Green Kubo relations, a transport coefficient is predicted based on the integrated ACF. Notably, this coefficient aligned closely with the total effective phase mobility computed using Darcy's equation for multiphase flow, particularly in scenarios where a linear relationship between flow rate and pressure gradient was observed. We provide the first experimental evidence of using FDT to determine transport coefficient during multiphase flow in porous media.
Our results open a new application for nonequilibrium thermodynamics where microscale fluctuations during multiphase flow are directly linked to macroscale parameters. Establishing a connection between these fluctuations and macroscale parameters is pivotal to understanding energy dissipation during multiphase flow and associated modes of transport.

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