Contribution ID: **262** Type: **Oral Presentation**

Derivation of 2-Phase Darcy Equations from Pore Scale Energy Dynamics using Non-Equilibrium Thermodynamics

Monday, 22 May 2023 10:50 (15 minutes)

The upscaling of 2-phase flow in porous media from pore to Darcy scale is a long-standing problem. While several approaches have been published in the literature, there remains no consensus on what the right approach is and what the correct Darcy scale transport equations are. Many approaches assume explicitly or implicitly that a length scale exists where pore scale dynamics average out such that equipartitioning of energy in the different degrees of freedom holds, which is sometimes referred to as the multi-phase representative elementary volume (REV). The implicit assumption is ergodicity where spatial, temporal, and ensemble averages are equivalent.

Many theoretical approaches explicitly require ergodicity, and few general strategies have been advanced to treat non-equilibrium thermodynamic behavior associated with non-ergodic systems. We develop a non-equilibrium theory using time-and-space averaging; assuming that ergodic conditions hold only at very small length scales. For instance, at late times Haines jumps travel beyond the range of diffusive mixing (which would be required for equipartitioning). Since the timescale for mixing is fast at small length scales, many non-ergodic systems can be described based on this approach. We show that fluctuations are constrained by the internal energy dynamics, deriving quasi-ergodic requirements that must hold for any stationary process due to conservation of energy. Since these requirements are formulated in terms of observable quantities, they can be used to explicitly identify the timescale where valid transport coefficients can be obtained. This result is significant because it provides a straightforward way to homogenize the dynamics of multiphase flow in porous media which does not obey equipartition of energy, particularly with slow fluctuations.

We apply our theory to derive transport coefficients for immiscible fluid flow through porous media, demonstrating that pressure fluctuations observed in experiments can be non-Gaussian due to cooperative effects that are caused by capillary events. We show that the macroscopic dynamics can still be homogenized if the timescale for averaging is chosen such that these fluctuations perform no net work on the system. We further demonstrate that changes to fluid topology are responsible for non-ergodic effects, and that time-and-space averages provide a natural mechanism to account for discrete changes based on the topological residence time associated with a particular micro-state of the system.

Following that methodology, we derive Darcy's law for single phase flow and the 2-phase Darcy equations for multiphase flow at stationary ("steady-state") conditions. The equations have the same form as the 2-phase Darcy equation introduced as a phenomenological extension to Darcy's law. Cross terms in relative permeability arise from having experimental access to phase pressures independently.

Participation

In-Person

References

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Session Classification: MS06-A

Track Classification: (MS06-A) Physics of multiphase flow in diverse porous media