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Non-Equilibrium Effects of Fines Migration in Porous Media Saturated with Immiscible Fluids

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Non-Equilibrium Effect in Particulate Transport: The notion of non-equilibrium (NE) thermodynamics in transport phenomena has been explained in detail in literature. In practice, many industrial and living systems that deal with transport of matter and of energy realize NE effects because of the interferences among complex sub-scale features in the system. Thus, inclusion of NE provides much accurate transport predictions for systems with significant gradients in velocity, pressure, and concentrations. In this study, we adapt the general form of harmonic oscillation equation to describe non-equilibrium (NE) effects in porous media. we proposed **Eq. 1** to explain NE and validated it with the results from COMSOL, Multiphysics software.

$$NE = Ae^{-\zeta\omega_0 t}\sin\left(\sqrt{1-\zeta^2}\,\omega_0 t+\varphi\right) \qquad \textbf{Eq. 1}$$

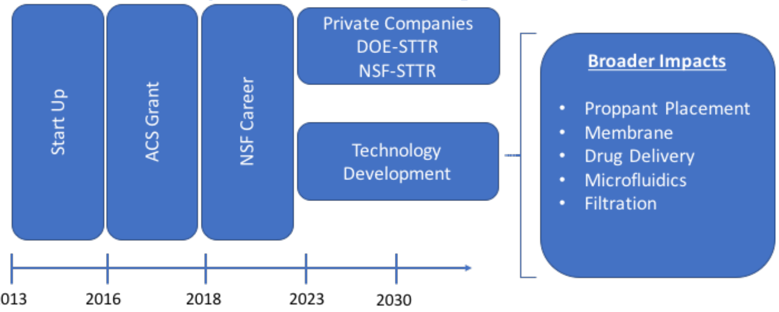
where A is amplitude representing the magnitude of NE, ζ is damping ratio representing time needed to attain equilibrium. The NE parameter is defined as function of local particle velocity (v_i^P) and fluid velocity (u_i^f)$[1-v_i^P/u_i^f\ ]$.. The NE effect is evaluated by solving coupled mass and momentum balance equations using computational fluid dynamic (CFD) module of COMSOL Multiphysics simulator. Sensitivity analyses are performed to account for particle size, fluid viscosity, and flow path geometry. MATLAB curve fitting tool is used to match the results obtained from the simulations with the harmonic oscillator equation. It is hypothesized that high amplitude implies large NE between particle and fluid, whereas low damping ratio indicates the longer time needed for the particle to reach equilibrium.

We considered three different simulation models: (1) straight tube, (2) simplified divergent-convergent tube, and (3) actual porous media obtained from SEM image. In all simulations, fluid velocity is calculated by solving Navier-Stokes equation for incompressible system. In the next step, the calculated fluid velocity values are used to determine particle velocity as a function of time and space.

Impact on PI's carrier and students: The PI's CAREER plan and the long-term outcome of the project is shown in Figure 1. After studying NE effect on particle transport in fluid flow, development of a new theory to explain NE effects in Particle-Particle-Fluid-Fluid flow systems is the PI's long-term goal. The proposed theory will characterize and evaluate NE effects because of Fluid-Fluid, Particle-Fluid, and Particle-Particle phenomena, separately as well as collectively. Thanks to generous ACS support, the PI could continue his research work and accomplish more than a dozen peer-reviewed journal publications such that he was granted the 2018 SPE Mid-Continent Regional Reservoir Description and Dynamics awards.

Our study suggest a reasonable match between predicted values obtained from **Eq. 1** and the COMSOL simulation results for the selected geometry (**Figure 1**). The implication of our finding is that the complex system of equations representing particulate flow can be simplified under certain conditions into flow equation and an evolution NE equation for particles. Hence, the distance travelled by x% of particles at any given time can be easily determined using NE evolution equation. Moreover, our study showed that NE effect can be decoupled into particle-particle , particle-fluid, particle-wall subcategories; however, Fluid-fluid NE effects were insignificant compared to other NE effects, in cases we studied.

Figure 1: The PI's career plan



The results indicate that the time variation of the NE effect complies with the theory of stability. Two key parameters of oscillator equation are amplitude (A) and damping ratio (ζ), where the former represents the magnitude of NE and the latter represents time needed to attain equilibrium. NE parameter in a diverging flow path illustrates an underdamped behavior (ζ less than 1). Reducing the fluid viscosity leads to a reduced ζ value indicating that it will take longer for particles to reach to equilibrium state.

However, reducing fluid viscosity yields an increased value of A indicating a larger magnitude of NE effect. For different particle sizes, our simulation results show that large particles have high amplitude and low damping ratio values. For converging flow path, the particles show an over-damped behavior (ζ greater than 1). The NE effect increases exponentially as a function of time implying that particle velocity always remains less than the fluid velocity; hence, the system will never achieve an equilibrium state. The flow simulation of SEM image shows consistent results with diverging and converging flow results as particles travels along pore network.

The outcome of this work can shed light upon explaining the complex NE effects in porous media. The generalized equation to model NE can help temporarily decouple particle transport equation from fluid equations facilitating much advanced particulate flow modeling in the large-scale problems.

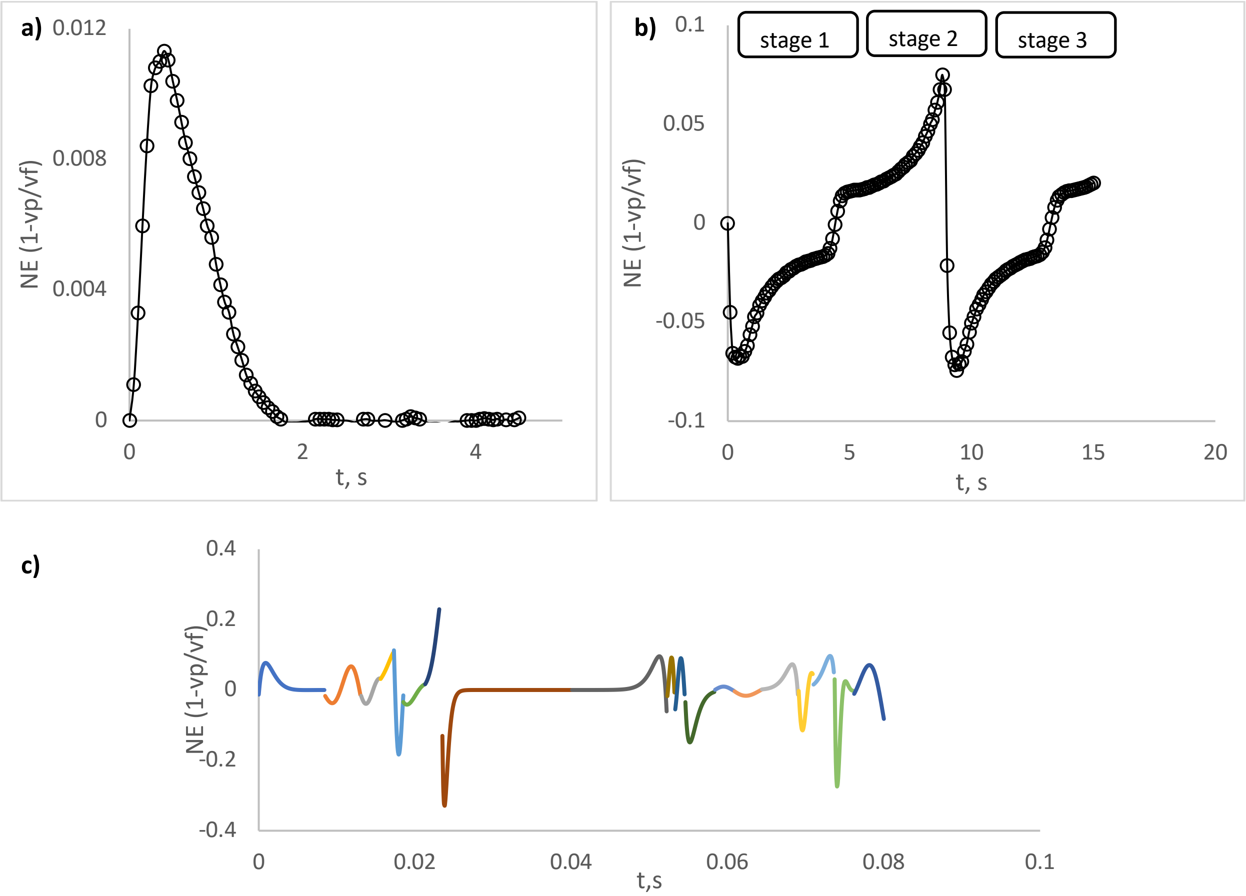


Figure 2. NE effect in a) straight tube b) divergent-convergent tube, and (3) porous media

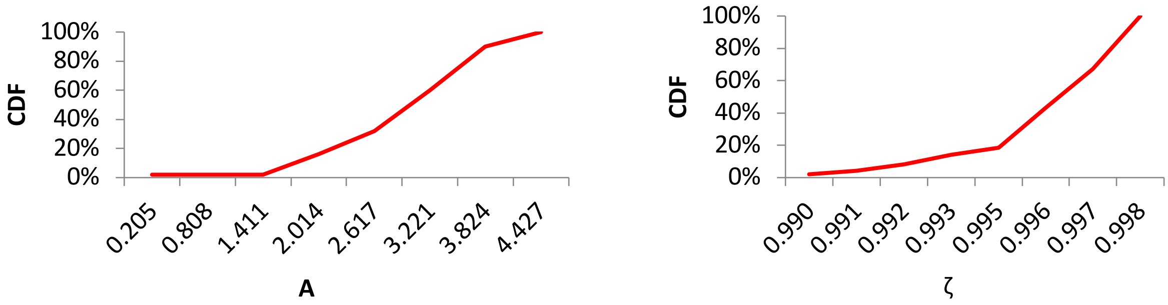


Figure 3. Cumulative distribution function for amplitude and damping ratio for divergent tubes