10 Effective Transport through Porous Media under Nonequilibrium Relaxation Conditions

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10.1 INTRODUCTION

Although the assumption of instantaneous equilibrium conditions is often made in modeling of phenomenological processes of porous media, many natural processes nevertheless undergo a gradual change owing to the requirement of a finite time for reorganization of the fluid system and species in porous media from one equilibrium state to another. For example, the freezing and thawing of moist soil is a gradual process occurring over a temperature range (Civan and Sliepcevich, 1985; Civan, 2000a) although many previous works casually assumed instantaneous freezing and melting of water at a constant temperature, such as 0°C at 1 atm. In reality, the equilibrium conditions can never be attained during the porous media transport processes when the magnitude of the relaxation time is larger than the governing process time. Einstein (1920) formulated the kinetics of nonequilibrium relaxation processes by a simple linear kinetics relationship, referred to as a constitutive equation. However, more rigorous constitutive relationships may be required for particular processes as described in this chapter.

Multiphase fluid and suspended-particulate transport through heterogeneous porous media may be affected significantly by the nonequilibrium relaxation processes of various orders of magnitudes depending on the prevailing conditions of fluids and porous media. When the prevailing conditions do not allow the establishment of local equilibrium conditions in porous media instantaneously, the conventional formulation of porous media transport requires an accommodation for various process delays in attaining equilibrium and their effects on the overall transport processes. For example, the redistribution of a multiphase fluid system in porous media may require a certain amount of characteristic time for rearrangement of the multiphase system to respond to local variations in flow conditions (Aryana and Kovscek, 2013). As another example, solid particles separated from a solution of a solute flowing through porous media may not be able to deposit over the pore surface immediately following the formation of the particulate matter such as the paraffin crystals separated from waxy oil (Ekweribe et al., 2009, Ekweribe and Civan, 2009, Michel and Civan, 2009a,b).

This chapter provides an overview of the available approaches, some new critical modifications made by the author himself, and their applications of practical importance with examples taken from the chemical, environmental, and petroleum engineering fields. Specifically, the following topics are reviewed, formulated, and illustrated:

- Separation of dissolved gas from oil and water
- Displacement of immiscible fluid phases in porous media
- Transport of dispersed wetting/nonwetting phases through porous media
- Permeability impairment in porous media by precipitate deposition
- Nonequilibrium modification of the gradient transport laws

Delays in degasification of the liquid phases are shown to yield less free gas than predicted under the equilibrium assumption. The redistribution of fluids in porous media is shown to affect the immiscible displacement processes significantly. The dispersions of gas bubbles in liquid phases and liquid droplets in gas phase or in another immiscible liquid phase are shown to cause delays in attaining equilibrium because of the time required for pore surface deposition and mobilization and pressure pulsations caused by dispersed particles passing through the narrow pore throats and subsequent jetting, deformation, and breakage of these particles. The permeability reduction is influenced by delays in the deposition of the particulates separated from a solution of solute. It is emphasized that the ever popular Darcy's law of flow through porous media requires a correction for delays caused in the transmission of the effect of fluid viscosity from the pore surface to the body of the pore fluid during fluid motion under unsteady-state conditions.

The treatise presented in this chapter provides valuable insights into the nature and formulation of gas separation, immiscible fluid displacement, and deposition, mobilization, and transport