Microporous and Mesoporous Materials 170 (2013) 299–317

Contents lists available at SciVerse ScienceDirect

Microporous and Mesoporous Materials

journal homepage: www.elsevier.com/locate/micromeso

Review

Osmosis in porous media: A review of recent studies

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ARTICLE INFO

Article history:
Received 23 June 2012
Received in revised form 1 October 2012
Accepted 6 December 2012
Available online 20 December 2012

Keywords:
Osmosis
Porous material
Flux
Conservation law

ABSTRACT

A concise review of recent theoretical and experimental studies of osmotic phenomena in porous materials is provided. Macroscopic models are presented and the determination of the involved transport coefficients is described. The focus is on the bulky media (as opposed to "thin" membranes) that are encountered in the fields like geophysics, environmental sciences, or civil engineering. A brief summary consisting of critical remarks and observations concerning the transport models and experimental methods is given in conclusion. Possible future investigations of the osmotic behavior of bulky porous materials not studied previously are outlined.

Contents

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1387-1811/$ - see front matter
http://dx.doi.org/10.1016/j.micromeso.2012.12.009

1. Introduction

Osmosis is a natural transport of water molecules across a selectively permeable material (acting thus as a membrane) that allows the migration of a solvent (usually water) and restricts the passage of solute molecules (salts) or ions (see Fig. 1). When such a material separates a solution with different solute concentrations, a fluid flows from the region with a low solute concentration (a high fluid chemical potential) to the region with its high concentration (a low fluid chemical potential) [1–8]. The flow increases the fluid pressure in the latter region (see Fig. 2) and decreases it in the former one. These pressure changes lead to a countering hydraulic flow, until the two opposing flows cancel each other and equilibrium is reached.

Osmosis can be caused not only by a concentration gradient (chemical osmosis) but also by gradients in the electric potential (electro-osmosis) or temperature (thermo-osmosis). In fact, an electric potential difference can force a fluid to flow into or out of the material [10–12]. In addition, under a temperature gradient, a fluid may flow from hot to cold region or vice versa [13,14], depending on the entropy difference between the fluid inside the material and outside it [15]. For example, water in a hydrophilic material can be considered to have a relatively ordered state compared to water existing outside the material, leading to a water flow from the cold side to the hot one [16]. On the other hand, for hydrophobic materials water usually flows in the opposite direction [16,17].

In this review paper we describe recent macroscopic models that have been recently applied to study the coupled phenomena related to osmosis in porous materials as well as the principles of experimental determination of the transport parameters associated with these models. We consider chemical osmosis, electro-osmosis, and thermo-osmosis separately. The review is restricted to bulky porous media, whereas "thin" membranes are not discussed. Moreover, certain specific topics, such as large deformations and concentration polarization effects, are also not considered.

As for the porous media, quite diverse types of materials have been studied so far, ranging from soils to biological materials. Nevertheless, an overwhelming majority of the studies deal with clays or porous materials similar to clays. This is very natural, given their great importance in various geophysical, environmental, or civil engineering applications. However, there are other large groups of porous materials, such as building materials, whose microscopic properties are very similar to those of clays and, hence, osmotic phenomena should be expected to play a significant role in the transport of solutes through them. As a result, if for such materials the osmotic modes of transport are not taken into account, the transport (or at least a part of it) is attributed to incorrect mechanisms, and serious inaccuracies can arise in modeling and interpretation of the transport. It is thus striking that only a small fraction of the studies have investigated osmotic phenomena in the porous materials other than clays, even though the corresponding results may be essential in various technical applications. Therefore, an aspiration of the review is to encourage and inspire further research in the areas where osmotic phenomena can be an essential ingredient in proper description of transport processes (but have been neglected), using theoretical and experimental methods recently applied for this purpose in similar areas of research.

The outline of the review is as follows. In Section 2 we first give a brief general survey of various studies of osmosis, physical background of the models used to this end, and also mention molecular simulations applied to investigate osmosis. For the reader's benefit, the classical models of osmosis are summarized in Section 3. Section 4 is the core of the review, providing recent macroscopic models and experimental techniques for the study of osmotic phenomena in bulky porous materials. It is divided into three parts in which chemical osmosis, electro-osmosis, and thermo-osmosis are dealt with separately. A short summary is given in Section 5, and suggestions for further research are pointed out in Section 6. Note that a list of frequently used physical quantities is added to allow the reader their quick identification and understanding of their physical meaning throughout the text.

Frequently used symbols

c_s	salt concentration (mol m^{-3})
D	diffusion coefficient (m^2 s^{-1})
F	Faraday constant (96 485 C mol^{-1})
g	gravitational acceleration (m s^{-2})
j_{tot}	total (volume) flux (m s^{-1})
j_s	molar solute (salt) flux (mol m^{-2}s^{-1})
j_w	molar water (solvent) flux (mol m^{-2}s^{-1})
k_e	electro-osmotic permeability (m^2 s^{-1} V^{-1})
k_h	hydraulic conductivity (m·s^{-1})
k_T	thermo-osmotic permeability (m^2 s^{-1} K^{-1})
P	hydraulic pressure (Pa)
q	heat flux (J m^{-2} s^{-1})
R	gas constant (8.314 J K^{-1} mol^{-1})
S_T	Soret coefficient (K^{-1})
T	thermodynamic temperature (K)
u_k	mobility of species k (m^2 s^{-1} V^{-1})
$\bar{V}$	partial molar volume (m^3 mol^{-1})
ε	material porosity (−)
κ	medium (intrinsic or Darcy) permeability (m^2), $\kappa = \mu_d k_h/\rho g$
λ	thermal conductivity (W m^{-1} K^{-1})
μ_d	dynamic viscosity (Pa s)
μ	chemical potential (J mol^{-1})
ν	van't Hoff factor of dissociation (−)
π	osmotic pressure (Pa)
ρ	solution (fluid) density (kg m^{-3})
σ	osmotic efficiency (reflection coefficient) (−)
σ_e	electrical conductivity (S m^{-1})
Ψ	electrical potential (V)
ω	solute permeability at zero volume flux (mol N^{-1} s^{-1})

2. General survey

2.1. Porous materials and applications

Various porous materials may act as semipermeable membranes, restricting the transport of solute more than the flow of solvent. Indeed, direct experimental evidence for osmosis was provided for clays, both in laboratory [3,6,18–26] and field