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Evolution of the effective permeability for transient and pore-scale two-phase flow in real porous media

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ABSTRACT

Permeability is one of the key parameters to model and predict the infiltration or transport process of fluid through a porous media. However, most models and approaches that have been developed experimentally, theoretically or numerically to determine the saturated permeability for steady flow are indirect or based on predefined or virtual porous media models. To the best of our knowledge, the variation behavior of the effective permeability with the infiltration length or time in unsaturated flow based on a real porous media has rarely been considered and is little understood. Herein, we propose a simple numerical method of modelling the infiltration processes of a liquid though a porous media preform based on a real porous media obtained from an experimental scanning electron microscopy (SEM) image and validate it by comparing the simulated results with experimental data. Then, we calculate the unsaturated permeability using Darcy's law based on the results of numerical simulation without any structural parameters of porous media. The evolution of the effective permeability with the time or flow front is then presented, and the relationship between the saturation degree and permeability is also considered. The numerical results indicate that (i) the maximum infiltration length along the macroscopic flow direction globally characterizes the variations of the flow front better than the other parameters; (ii) the effective permeability of an unsaturated porous media decreases exponentially with time and the advancing of the flow front and decreases with the degree of saturation following a power-law trend; and (iii) the saturation evolution may have great effects on the effective permeability of a liquid through a porous media.

1. Introduction

The infiltration process of a liquid through a porous media is a very interesting issue in a wide range of academic disciplines and engineering areas, including but not limited to geophysics, chemical engineering, agricultural and environmental protection, and materials and medical science [1–4]. A great number of advanced manufacturing techniques for discontinuously reinforced metal matrix composites, which are multi-phase systems that consist of a metallic matrix and dispersed inorganic component, have been fully developed based on the infiltration process of a liquid through a porous media. At present, much more attention from researchers has been focused on liquid composite moulding processes (LCM) characterized by significant potential at low cost [5]. The process is strongly dependent on the internal morphology of the porous media, and almost all the infiltration processes must take into account how easily the flow passes through the porous media and how the flow is expanded in the internal structure of the porous media on the microscopic scale, viz., complex and complicated flow patterns exist within the pores and between the grains of porous media materials [6]. The effect can be described at a macroscopic level using the effective permeability parameter, which synthetically represents the ability of the porous media to transmit fluid driven by a pressure gradient and is related to the porous media structure, such as the porosity, pore shape, pore distribution and tortuosity [7]. In most cases, the permeability is one of the key and indispensable parameters to describe the macroscopic infiltration properties of porous media in both numerical simulation and theoretical analysis, such as Darcy's law and the Brinkman equation [8]. However, a quantitative and explicit characterization by means of physical interpretation is difficult because of the complexity of the pore shapes and aperture connectivity. It has been

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Nomenclature

p	pressure of fluid in REV
P	pressure of fluid in porous media preform
$\boldsymbol{u}$	actual fluid flow velocity
$\boldsymbol{U}$	Darcy flux
w	width of porous media preform
h	height of porous media preform
l	length of porous media preform
P_{out}	outlet pressure of porous media preform
P_{in}	inlet pressure of porous media preform
t	time
$\boldsymbol{F_{st}}$	interfacial tension force
$\boldsymbol{n}$	interface normal vector
L_0	length of REV
H	height of REV
E	minimal distance function
H_e	Heaviside function
H_{sm}	smeared-out Heaviside function
s	specific surface area
C	Carman-Kozeny factor
d	mean pore diameter of porous media
D	mean solid particle diameter of porous media
S	saturation degree
p_{in}	inlet pressure of REV
p_{out}	outlet pressure of REV
L	infiltration length
q	total sum of fluxes at inlet
c_0	Kozeny constant

Greek symbols

ξ	interface thickness
κ	permeability of porous media
ν	kinematic viscosity
φ	porosity of porous media
ρ	density
Ω	time-independent domain
Γ	interface front of fluid
Φ	level set function
$\boldsymbol{\alpha}$	tangential tension tensor
δ	a type of delta function
λ	property for given fluids
μ	dynamic viscosity
γ	amount of initialization
ε	hydraulic tortuosity
τ	artificial time

Subscripts and superscripts

i	phases, $i = 1, 2$ refer to liquid and gas phases, respectively
m	different values, $m = 1, 2, 3$ refer to minimum, mean and maximum, respectively
T	transpose operation, time

Special symbols

∇	spatial deviation
$\lvert\cdot\rvert$	norm of physical quantity
Δ	difference of physical quantity
∂	partial derivation of physical quantity
$\partial\Omega$	boundary of solid particles and domains

an old and open challenge for scientists to relate the direct features of a porous media to the permeability without conducting expensive or time-consuming experiments [9]. Therefore, this paper describes the first steps required to numerically investigate the flow behavior in porous media that exist in LCM or other fields to allow better permeability determination.

The concept of permeability, which may be understood to be a measure of the flow conductance of porous media, was introduced in early studies carried out by Henry Darcy, who investigated the resistance of a fluid to flow through a solid matrix [10]. According to the concept of the effective permeability, one can define the permeability in basically two forms. One form is presented in Eq. (1), also known as Darcy's law, which denotes that the mass flow rate and the pressure gradient are related by the viscosity of the fluid and permeability. From the viewpoint of hydrodynamics, this expression is only an external manifestation of the permeability of the porous media and has been shown to be deducible from the Navier-Stokes equations using the homogenization technique, and the equation holds only when the flow is in the creeping regime.

$$\boldsymbol{U} = -\frac{\boldsymbol{\kappa}}{\mu}\nabla p \tag{1}$$

where κ (m^2) is the permeability of the medium, μ (Pa·s) is the viscosity of the fluid in the porous medium, ∇p (Pa/m) is the pressure gradient vector, and $\boldsymbol{U}$ (m/s) is the flux (volumetric flow rate per unit area, cross-section-averaged fluid speed). The value of this flux, often referred to as the Darcy flux, is not the velocity at which the fluid is travelling through the pores. Instead, the actual fluid flow velocity $\boldsymbol{u}$ (m/s) is related to the Darcy flux $\boldsymbol{U}$ via the porosity (φ) of the porous medium, viz., $\boldsymbol{u} = \boldsymbol{U}/\varphi$. Most permeability determination methods use this form because the flow rate and pressure may be measured easily by experiments.

The other form is demonstrated in Eq. (2), also known as the Kozeny-Carman (KC) equation [11], which denotes that the permeability is presumably independent of the flow conditions, such as the flow rate and pressure, based on the assumption of a Poiseuille flow through a capillary bundle for porous media. From the viewpoint of the material structure, this form demonstrates that the permeability is an intrinsic characteristic of porous media, independent of the hydrodynamic behaviors. Though the KC equation is seldom employed in experiments because the tortuosity is not a well-defined control parameter, some empirical formulas, e.g., the Blake-Kozeny, Carman-Kozeny, and Rumpf-Gupte formulas, have been derived for predicting the permeability based on the form in porous media. The principal limitation of the CK equation is that all the geometrical features of the preform are lumped into the CK factor, and it is well-known that there is no unique permeability-porosity relationship that can be applied to all porous materials [12]. Therefore, many modifications have been carried out based on the CK equation, and these empirical formulas give the relations between the permeability and porosity of porous media [13], as listed in Table 3.

$$\boldsymbol{\kappa} = c_0\frac{\varphi^3}{s^2\varepsilon^2} \tag{2}$$

where s is the specific surface area, c_0 is a dimensionless Kozeny constant that depends on the microchannel geometry, and ε is the hydraulic tortuosity, which is the ratio of the mean length of the true fluid particle flow paths to the straight-line distance through