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Experimental and numerical investigations on the flow around and through the fractal soft rocks with water vapor absorption

Y.J. Zhuang [a,c], H.Z. Yu [b], Q.Y. Zhu [a,c,*]

[a] School of Engineering, Sun Yat-sen University, Guangzhou 510275, China
[b] China Earthquake Networks Center, Beijing 100045, China
[c] Guangdong Provincial Key Laboratory of Fire Science and Technology, Guangzhou 510275, China

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ABSTRACT

Previous studies show that the rock–water interaction is one of the critical scientific issues for the soft rocks engineering. In this work, we propose a numerical model to study the flow across a hygroscopic rock cylinder subjected to a uniform flow of vapor–air mixture. To better understand the characteristics of water vapor absorption, dynamic moisture absorption measurements are carried out and a fractal model to describe the particle size distribution (PSD) of the soft rocks is presented. The time-dependent Navier–Stokes equation and the Darcy–Brinkmann–Forchheimer model are respectively adopted for the homogenous fluid region and the porous rock region, while the energy and species equations are used for both the porous and fluid regions. Based on the high order compact finite difference schemes with body-fitted grids, a single-domain approach is devised from above governing equations to describe the flow in both the porous and fluid regions, in which the effects of the hygroscopicity, the fractal dimension, the Darcy and Reynolds numbers on the streamline, flow separation, concentration field and thermal field can be evaluated in detail. Our preliminary simulations show that the hygroscopicity, which suppress the occurrence of recirculating (i.e. the critical Reynolds number of a recirculating wake becomes higher), may have a slight effect on the flow behind the porous rock cylinder in the beginning, and dribble away with increase of the time frame. Specially, the higher the fractal dimension (D), the lower the penetrability and hygroscopicity of soft rocks; the higher the Darcy number (Da) and Reynolds numbers (Re), the more penetration of the flow pattern, thermal field and moisture sorption inside the cylinder as well as the larger size of the concentration plume in the elongated recirculation region. This may help us establish a physically reasonable methodology to systemically assess fluid flow in soft rocks.

1. Introduction

Soft rocks are widely used in many aspects of mine engineering, geological engineering and underground engineering [1–3]. In recent years, many studies estimated the characterization of the isotherms and kinetics of water vapor sorption on soft rocks [4,5]. Moisture may cause the damage on soft rocks, such as salt crystallization, chemical and biological attack, wind erosion, and high heating energy consumption, which results in a significant reduction in the mechanical properties of soft rocks. Thus, studies on the interaction between soft rocks and water have attracted considerable attention [6,7].

Guo [8] did a series of water absorption tests on dried soft rocks and found that the mineral content, the effective porosity and the fractal dimension were the main factors dominating soakage capacity. In fact, different microscopic pore structures and particle size distribution (PSD) of soft rocks have different retention forces and grabability for fluid when water vapor flows through the pores. Earlier work by Turcotte [9] showed that the PSD in the rock materials has fractal property. Tyler [10] also developed a mass-based distribution to estimate the fractal dimension of PSD. In recent years, the possibility of characterizing PSD and pore size distribution of rocks using fractal theory has been developed by Billi [11], Heathman [12], Zhang [13], Yu [14], Jiang [15] and others. Besides, Schlueter [16] carried out the scanning electron microscope (SEM) experiment to estimate the fractal dimension of pores in sedimentary rocks and discussed the influence of fractal dimension on permeability. These results indicate that fractal theory is a useful tool in quantifying pore structures, PSD, as well as, rocks permeability to study the transport properties of porous soft rocks [17–19].

Also in the viewpoint of fluid mechanics, the fractal characteristics of PSD can be verified by studying the fluid flow over the rock samples. The flow around the cylinders has been extensively

* Corresponding author at: School of Engineering, Sun Yat-sen University, Guangzhou 510275, China.

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Nomenclature

a	radius of the cylinder (m)
C_s	mass fraction of water vapor in the rock sample (kg m^{-3})
c_s	heat capacity of soft rocks (J kg^{-1} K^{-1})
C_v	mass fraction of water vapor in the air filling the inter-particles void space
c_m	heat capacity of the vapor–air mixture (J kg^{-1} K^{-1})
c_{pa}	heat capacity of air (J kg^{-1} K^{-1})
c_{pv}	heat capacity of water vapor (J kg^{-1} K^{-1})
D	fractal dimension
Da	Darcy number
D_v	diffusion coefficient of water vapor in the air of the hygroscopic porous rock particles webs (m^2/s)
D_s	diffusion coefficient of water in the rock sample (m^2/s)
G	Forchheimer coefficient
J	Jacobi transform operator
K	permeability
k	a constant
K_{mix}	total effective thermal conductivity (W m^{-1} K^{-1})
K_s	effective thermal conductivity of soft rocks (W m^{-1} K^{-1})
K_{va}	effective thermal conductivity of vapor–air mixture (W m^{-1} K^{-1})
M_a	molecular weights of air (kg/kmol)
M_v	molecular weights of water vapor (kg/kmol)
$M(R)$	cumulative mass of particles with the size smaller than R
M_s	total mass of all the particles (kg)
M_t	mass gain at a specific time (g)
M_∞	mass gain after infinite time (g)
$\dot{M}$	absorption rate of the porous media
M_i	the mole fraction of the ith component
$N(R)$	number of rock particles whose size is greater than R
$N'(R)$	number of rock particles whose size is smaller than R
p	pressure (Pa)
p_{vs}	equilibrium pressure of water vapor (Pa)
R_{av}	average rock particle radius
RH	relative humidity
R_M	largest particle in the rocks
R_0	a characteristic size
r	radial coordinate in a rock particle
R	perfect gas constant
Re	Reynolds number
T	absolute temperature (K)
T_0	indoor temperature (K)
t	time (s)
U	free-stream velocity (m/s)
$\vec{V}$	flow velocity vector (m/s)
V_p	skeleton volume (m^3)
V_s	pore volume (m^3)
W_s	water content in the rock sample
W_d	dry weight (kg)
W_w	wet weight (kg)
x	x-coordinate
y	y-coordinate

Greek symbols

λ	heat of sorption of water vapor by rocks (kJ/mol)
κ	thermal diffusivity (m^{-2} s^{-1})
ρ_m	fluid density (kg/m^3)
ρ_s	density of rock sample (kg/m^3)
ε	porosity of the porous media
α	a boundary-fitted coordinate operator
β	a boundary-fitted coordinate operator
γ	a boundary-fitted coordinate operator
μ_m	fluid dynamic viscosity (kg m^{-1} s^{-1})
ξ	mapping of x-direction
η	mapping of y-direction
τ	mapping of t

studied for a long time with the structural design usually being circular and square shapes [20,21]. Although the shape is simple, it offers rich fluid mechanics features of flow separation, wake formation, vortex shedding, heat transfer etc. In general, the Darcy law and the asymptotic equation of Stokes were used to govern the flow in porous and non-porous regions. For example, Joseph [22] examined the low Reynolds number flow of viscous fluid around a porous sphere. Noymer [23] computationally and experimentally investigated the steady flow past permeable cylinders at moderate Reynolds numbers. Dhinakaran [24] studied the flow and heat transfer from an isolated square cylinder to a flowing fluid. Recently, a number of investigators studied the flow around and through a porous cylinder using the Darcy–Brinkmann–Forchhei mer model. Bhattacharyya [25] studied the fluid motion and solute transport around and through a porous cylinder. Yu [26] performed numerical simulations for the flow past and through a porous square cylinder and found that the size and the location of the wake mainly depended on Re and Da. Al-Sumaily [27] numerically simulated the forced convective flow over a circular cylinder in the porous-material filled channel. Valipour [28] used the finite-volume method (FVM) to study the flow around and through a porous diamond cylinder. Shokri [29] presented numerical simulations on the fluid flow and forced convection heat transfer around a solid cylinder wrapped with a porous ring.

More recently, Zhu [30] provided high order accurate compact difference schemes to discuss the flow of a vapor–air mixture around and through a hygroscopic porous fiber cylinder. In their study, the effects of absorption, Reynolds and Darcy numbers on the flow pattern were investigated in detail. However, the interaction between the concentration field of water–vapor and thermal field were not involved, offers little information on the evaluation of the relationship between the external flow around and the internal flow within the porous cylinder, which is of great practical importance in the absorption process on soft rocks.

In this paper, dynamic moisture absorption measurements and X-ray diffraction (XRD) analysis are firstly performed to examine water vapor absorption characteristics, then we attempt to propose a numerical model to study the flow of a vapor–air mixture around and through the hygroscopic fractal porous soft rocks. The effects of fractal dimension, hygroscopicity, Reynolds and Darcy numbers on the flow pattern, moisture transfer and thermal field are exactly the focus of the present work. In the calculation, the third-order Runge–Kutta method and the high accuracy compact difference schemes are used [31]. Along with the numerical studies, scanning electron microscope (SEM), and infrared camera experiments on soft rocks samples are also conducted to validate the model and numerical results.

2. Mathematical model

The rock samples used in this paper were collected from different depths in the land near Guangzhou South Railway Station, Guangzhou city, China. Fig. 1a shows a cylindrical rock sample and its computational domain. We assume that the cylinder of radius a is hygroscopic, which is placed in a two-dimensional, laminar, unsteady and uniform flow of a vapor–air mixture.