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A lattice Boltzmann model for heat and mass transfer phenomena with phase transformations in unsaturated soil during freezing process

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ABSTRACT

In this paper, a mesoscopic numerical model for simulating the heat and moisture transport phenomena in frozen soil during freezing process is presented. The model includes a stochastic generation-growth method for reconstructing the soil structure with given macroscopic geometric parameters, a lattice Boltzmann method (LBM) model for solving multiphase fluid flow and a LBM model for solving heat conduction with phase change in porous media. By using the present model, freezing process in sandy loam soil is demonstrated. Two types of boundary condition, prescribed temperature and adiabatic boundary conditions are employed in the given cases. All the numerical results show good agreement with experimental results. Considering the mesoscopic nature of LBM, the proposed model is a potential alternative to traditional continuum models.

1. Introduction

Frozen ground region is generally distributed on earth. Permafrost region covers approximately 23% of the global land surface; seasonally frozen ground region can be found all over the regions above 24° latitude [1]. The freezing–thawing process of frozen soil has great effects on regional climate and hydrology [2,3]. Moreover, the abundant greenhouse gases in frozen soil are also important to global warming [4,5]. However, the coexistence of heat and mass transfer, phase change and multiphase flow during the freezing–thawing process makes it considerably difficult to give a simple and complete description of water content and temperature distribution in frozen soil. Therefore, a favorable heat and moisture transfer model shows its great importance to frozen soil research.

The coupled heat and mass transport process was introduced into frozen soil model to solve the heat and moisture balance problems in the early 1970s [6–8]. In the earlier studies, certain processes, for instance, vapor flux and its corresponding phase change were omitted for simplicity [6–9]. During the past decades, more evidence revealed the complexity of heat and mass transport in freezing–thawing process of frozen soil [10–12]. Thus far, various numerical models with different levels of complexity have been developed. In term of governing equations, the most complex as well as the most comprehensive model includes ten variables determined by four prognostic equations and five diagnostic equations with one assumption [11–13]; in the relatively simple model which is the most commonly used, only two prognostic equations are used for solving temperature and liquid water content. In term of physical processes, some models take into account the vapor movement and its corresponding phase change in the water and heat balances [10,14] while others neglect those processes [15–17]. Furthermore, even with the most complex model, the estimation of ice content and position of the ice lens remains a challenging task. One reason is the highly nonlinear relationship between temperature, ice content and liquid water content [13]. On the other hand, fundamentally, soil is granular porous material. Considerable research shows that the heat and mass transport in porous material is strongly affected by its pore structure [18–20]. The underlying problems raise the need for alternative approaches to understand the connection between the macroscopic phenomena and the underlying microscopic dynamic at a more fundamental level [21].

The conventional numerical methods such as finite difference method (FDM), finite element method (FEM) and finite volume method (FVM) are based on the discretization of macroscopic continuum equations. This scheme makes conventional numerical methods face great challenges while solving flow with complex interface or flow with complex boundary. Since the late 1980s, a new mesoscopic method base on the discrete kinetic theory, named the lattice Boltzmann method (LBM), has become a promising tool for the investigations of a wide range of complex flows, including multiphase flows, porous flows, thermal flows and reactive transport [22]. The fundamental idea of LBM is quite

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Nomenclature

c	lattice speed
c_s	speed of sound
C	specific heat
$\mathbf{e}$	discrete velocity
f	density distribution function of fluid lattice
f_1	liquid fraction
$\mathbf{F}$	force
g	density distribution function of thermal lattice
$\mathbf{g}$	gravitational acceleration
g'	sum of unknown distribution functions
G	adjustment coefficient
H	enthalpy
L	latent heat
s	tag variable
t	time
T	temperature
$\mathbf{u}$	velocity
$\mathbf{u}'$	common velocity of the fluid mixture
ΔV	difference of volume
x, y	axial coordinate
$\mathbf{x}$	lattice site
y_0	axial coordinate of boundary
α	thermal diffusivity
χ	mass fraction
Δt	time step
Δx	lattice spacing
ε	porosity
ε_0	given porosity
ν	kinematic viscosity
ρ	density
ρ_0	given density
τ	relaxation time
φ_d	core distribution probability
φ_g	growth probability
ψ	effect mass
$\boldsymbol{\psi}$	water potential
ω	weight factor

Superscripts

ads	adhesive force
b	body force
coh	cohesive force
eq	equilibrium state
k	number of iteration
tmp	temperature

Subscripts

A	air pressure
i	index of speed direction of lattice
l	liquid state
P	pressure
s	solid state
S	osmotic
Tot	total
tmp	temperature
Z	position
α	thermal conductivity
σ	first phase
$\bar{\sigma}$	second phase
ν	kinematic viscosity

straightforward: the macroscopic dynamics of fluid are the result of the collective behavior of many microscopic particles in the system and the macroscopic dynamics are not sensitive to the underlying details in microscopic physics [23]. Thus, LBM can be considered as a bridge sitting in the intermediate area between microscopic molecular dynamics and macroscopic fluid dynamics. The major advantage of LBM is that it behaves like a solver for the conservation equations in the bulk flow, meanwhile the kinetic equation offers many advantages of molecular dynamics, including clear physical pictures, easy implementation of complex boundary conditions and fully parallel algorithms [22].

In this work, an advanced mesoscopic numerical model based on LBM for simulating the heat and mass transfer phenomena with phase transformation in frozen soil during freezing process is presented. The fundamental idea of the proposed model is analogous to LBM: the complex phenomena in frozen soil during freezing process are caused by the interactions between several common physical phenomena and the stochastic structure of soil. The model is validated by comparing the numerical results with existed experimental results. This model should not only provide an advanced tool for the frozen soil research but also for the investigation of the similar process in generalized porous media as well.

2. Numerical models

2.1. Reconstruction of soil structure

In nature, soils are heterogeneous assemblies of materials, forming porous media [24]. Various studies have shown the importance of the stochastic approaches for flow, heat transfer and solute transport in porous media [24–26]. In this paper, a stochastic generation-growth method is adopted for soil structure reconstruction based on the given porosity. The reconstruction process is conducted as follows:

(i) Randomly locate the growing cores based on a given core distribution probability φ_d. The value of φ_d represents the quantity of particles in soil and further determines the size of particles at a given porosity ε_0.
(ii) Define the growing probability of growing cores in each direction $\varphi_{g,i}$. For a D2Q9 lattice Boltzmann model, there are 8 directions on the growing cores according to the velocity directions of a D2Q9 lattice.
(iii) Grow particles from the cores along the given directions; the newly grown particles are used as growing cores in the next cycle; calculate porosity ε, stop growing once ε meets the given porosity ε_0, otherwise go back to step (i).
(iv) For some critical circumstances, e.g. for the permeable structure with low porosity, an extra step is executed to identify connected regions. If the model meets the requirement, stop growing, otherwise go back to step (i).

Thus, for an area of a given size, the quantity of particles is determined by φ_d. The shape of a particle is defined by φ_g, isotropic distribution gives the particles round-like shape; anisotropic distribution gives the particles square-like shape, triangular-like shape or fiber-like shape as illustrated in Fig. 2. Therefore, by using a combination of different φ_g, a soil model with more realistic structure can be generated. Substantially, for the D2Q9 model, the generated soil structure is a $D(4, 8^2)$ bond percolation network. The first row of Fig. 1 illustrates the soil structure generated in 300×300 grids while the second row shows the connectivity of