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Numerical simulation of mass and heat transfer between biochar and sandy soil

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ABSTRACT

Biochar is a very important soil amendment in improving soil water retention. A multi-scale mathematical model was developed for investigating heat and mass transfer between unsaturated sandy soils and biochar. As both the sandy soil and the biochar were porous media, a water equilibrium model was set up based on existing experimental results. One-dimensional numerical simulation in unsteady state was conducted for obtaining the water content distribution in the biochar and the sandy soil. The numerical results agreed well with the experimental data, verifying this mathematical model can be used to evaluate the effects of biochar on sandy soil water retention. The effects of the environmental conditions, such as the relative humidity and the mass transfer coefficient (*Hm*), on the sandy soil water retention with biochar added, were further evaluated by the mathematical model. The numerical results showed that the application of biochar would be more effective in areas where soil evaporation was very strong.

1. Introduction

Biochar is the carbon-rich solid by-product from biomass pyrolysis. It usually has a large specific surface area, high porosity and a high level of resistance to be mineralized to CO_2 [1,2]. As a kind of porous media, biochar has been found to have a strong water holding capacity [3]. The application of biochar as a kind of soil amendment can significantly improve soil water retention ability [4,5]. This is especially of great significance in China. As the most populous country in the world, the land suitable for crop cultivation is very limited due to the shortage of water and rainfall in some areas. By the end of 2009, the desertified land area is up to 27.33% of the national territory and the sandified land area is up to 18.03% of the national territory [6]. Urgent efforts are required to improve the soil water retention in these areas. Though the biochar has proved capable of increasing the soil water retention, there are many factors, such as the properties of the biochar, the biochar adding ratio and adding methods, the hydraulic properties of the soil and the environmental conditions that can influence the effects. Though some experimental work has been done on this aspect [5,7], it is still not clear how these factors influence the mass and heat transfer between the biochar and the soil. Because both the biochar and the soil are porous media, the multi-phase mass and heat transfer between them are very complicated, compared with just one kind of porous media. In addition, it also involves the two-phase flow (liquid and the water vapor) and the water equilibrium between the two porous media (Table 1).

In the past several decades, complex theories have been developed to describe the heat and mass transfer in unsaturated porous media. Philip and De Vries [8,9], Luikov [10,11], Whitaker and Slattery [12–14] made a great contribution to the establishment of the models. Whitaker [15] introduced a volume average method to deal with the fluid flow and heat transfer in the porous media as a continuum. This method has been widely used in many fields, for example, the convective drying in packed bed for food, agricultural products or coal [16–19], soil science [20,21], heat pipe [22], etc. These models used mass, momentum and energy conservation equations to simulate the water and vapor mass transfer and heat transfer within the porous media. There are some models [23–25] that have been proposed to deal with heat and mass transfer in heterogeneous porous media. However, the properties of the sandy soil and the biochar are very different. The heterogeneous phenomenon only needs to be considered at the boundary.

In this research, a mathematical model was established based on our previous experimental results to simulate the heat and mass transfer between the biochar and the sandy soil. A water equilibrium model was also developed. With some assumptions, the models were simplified to one dimension for simple calculation. Then the simulation results were compared with those obtained from experiments to evaluate the models. Finally, the influences of the different factors were discussed based on the calculation.

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Nomenclature

AH	absolute humidity (g m^{-3})
RH	relative humidity (kg kg^{-1})
C_p	specific heat (J kg^{-1} K^{-1})
D	diffusivity (m^2 s^{-1})
g	acceleration of gravity vector (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
Hm	mass transfer coefficient (m s^{-1})
H	the depth of the sandy soil (m)
H_i	the depth of the i-th layer of the biochar
k	intrinsic permeability (m^2)
k_{rl}	relative permeability
M	molecular weight (kg mol^{-1})
n	the number of biochar in each layer
P	pressure (N m^2)
P_∞	ambient pressure (N m^2)
R	universal gas constant (J K^{-1} mol^{-1})
R_p	particle Radius (m)
S	saturation
S_A	cross sectional area of the container
T	temperature (K)
T_∞	ambient temperature (K)
V	velocity (m/s)
v	volume (m^3)
X	moisture content (kg kg^{-1} DW)

Greek Letters

ε	volume fraction
τ	time (s)
ρ	density (kg/m^3)
ρ_∞	density of the water vapor in ambient (kg/m^3)
μ	dynamic viscosity (kg m^{-1} s^{-1})
γ	latent heat of vaporization (J kg^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
ω	mass rate (kg m^{-3} s^{-1})

Subscripts and Superscripts

α	phase α
a	air
C	char
c	capillary force
eff	effective
g	gas mixture
l	liquid free water
S	sandy soil
s	solid
v	vapor

2. Mathematical modeling

In the previous research, the biochars' effects on water evaporation a in sandy soil was investigated by the experiments [26]. Four kinds of biochars [3] (Y450, Y550, S450 and S550) were mixed with the sandy soil uniformly. The height of the sandy soil column (bottom sealed) was 15 cm with a radius of 5.5 cm (Fig. 1). In the experimental tests, 200 ml of water was added to the mixture to simulate one rain fall or one irrigation performance. Each mixture was then weighted every 24 h to measure the water loss because of the evaporation. The details of the experiments could be found in the previous research [26]. To simulate the heat and mass transfer between biochars and the sandy soil, the mathematical model was developed based on the experiments.

2.1. Governing equations

To simplify the mass and heat transfer in the sandy soil and the biochar, the following assumptions are considered in the model: (1) The biochar particles are spherical with a uniforml size of 4 mm in diameter. (2) The biochars are evenly distributed in fourteen layers in the sandy soil column and take no volume in the sandy soil. The distance between each layer is 1 cm. (3) The surface of the biochar is in the same environment of the sandy soil, such as the water density, gas density and so on. (4) The hydraulic properties of the sandy soil and other conditions within the biochar particles are independent of angle. One-dimensional mathematical model can be used to describe the mass and heat transfer processes. For the particles, one dimension would be the radial coordinate. But for the column, the one dimension would be the height along the cylinder. (5) The three phases in the sandy soil and the biochar are solid (s), liquid free water (l), and gaseous phase (g). The gaseous phase consists of dry air and water vapor. (6) The gaseous phase can be treated as the ideal gas. (7) The densities of the liquid free water and solid are constant. (8) All phases in the same point have the same temperature. (9) The water contents of the biochar and sandy soil are proportional to their porosities when they are in the state of equilibrium (based on previous experimental results [26]).

The volume average method of Whitaker is used to define the averaged quantities. The phase average is defined as follows,

$$\langle\psi_\alpha\rangle = \frac{1}{v}\int_v \psi_\alpha dv \tag{1}$$

The intrinsic phase average could be obtained from,

$$\langle\psi_\alpha\rangle^\alpha = \frac{1}{v_\alpha}\int_{v_\alpha} \psi_\alpha dv = \frac{1}{v_\alpha}\int_v \psi_\alpha dv \tag{2}$$

$$\langle\psi_\alpha\rangle = \varepsilon_\alpha\langle\psi_\alpha\rangle^\alpha \tag{3}$$

where

$$\varepsilon_\alpha = v_\alpha/v \tag{4}$$

The sum of the volume fractions of the three phases is equal to 1, i.e.,

$$\varepsilon_s + \varepsilon_l + \varepsilon_g = 1 \tag{5}$$

The continuity equations for the three phases are as follows,

For the liquid phase,

$$\frac{\partial}{\partial\tau}(\langle\rho_l\rangle^l\varepsilon_l) + \nabla\cdot\langle\rho_l\rangle^l\varepsilon_l\langle V_l\rangle^l = -\omega \tag{6}$$

where ω is the liquid/vapor phase change flux mass rate.For the dry air the gas phase

$$\frac{\partial}{\partial\tau}(\langle\rho_a\rangle^g\varepsilon_g) + \nabla\cdot\langle\rho_a\rangle^g\varepsilon_g\langle V_a\rangle^g = 0 \tag{7}$$

For the vapor in gas phase

$$\frac{\partial}{\partial\tau}(\langle\rho_v\rangle^g\varepsilon_g) + \nabla\cdot\langle\rho_v\rangle^g\varepsilon_g\langle V_v\rangle^g = \omega \tag{8}$$

$$\langle\rho_v\rangle^g = \langle P_v\rangle^g M_v/(RT) \tag{9}$$