Experimental Thermal and Fluid Science 35 (2011) 1530–1534

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

The experimental investigation of heat transport and water infiltration in granular packed bed due to supplied hot water from the top: Influence of supplied water flux, particle sizes and supplied water temperature

Seksan Suttisong, Phadungsak Rattanadecho *

Research Center of Microwave Utilization in Engineering (R.C.M.E), Department of Mechanical Engineering, Faculty of Engineering, Thammasat University (Rangsit Campus), Pathumthani 12120, Thailand

ARTICLE INFO

Article history:
Received 14 December 2010
Received in revised form 11 July 2011
Accepted 15 July 2011
Available online 28 July 2011

Keywords:
Water infiltration
Temperature distribution
Granular packed bed

ABSTRACT

In the present study an experimental investigation of heat transport and water infiltration in granular packed bed (unsaturated porous media) due to supplied water flux is carried out. The study is focus on the one-dimensional flow in a vertical granular packed bed column assuming local thermal equilibrium between water and particles at any specific space. This experimental study described the dynamics of heat transport and water infiltration in various testing condition. Experimentally, the influences of particle sizes, supplied water flux and supplied water temperature on heat transport and water infiltration during unsaturated flow are clarified in details. The results showed that the granular packed bed with larger particle size results in faster infiltration rate and form a wider infiltration depth. Furthermore, the increase of the supplied water flux and supplied water temperature corresponds to faster infiltration rate, but the results not linearly related to the interference between the heat transport and hydrodynamics characteristics in granular packed bed.

1. Introduction

Water infiltration is an important process in many fields such as in the fields of hydrology, soil science, agriculture, civil engineering, and chemical engineering. Infiltration characteristics of water are of prime interest for a variety of concerns, including water conservation, flooding, runoff, erosion, recovery of isothermal energy, temperature control of soil and food preservation process. The infiltration of water is affected by several intrinsic and extrinsic factors. The intrinsic factors affecting the infiltration of water are the hydraulic conductivity function, water retention characteristics and porosity of media. The extrinsic factors mainly refer to climatic conditions, such as water flow pattern, ambient temperature, water flow rate and surface tension.

In the past few decades, the infiltrations of water have been studied by several researchers. Abriola and Pinder [1] proposed an infiltration model of porous media contamination by organic compounds. And they were considered the effects of matrix and fluid compressibilities, phase composition and mechanism of driving forces, i.e., capillarity, diffusion and dispersion. Stauffer and Dracos [2] presented the experimental and numerical study of water and solute infiltration in layered porous media which restricted to two-dimensional flow in a vertical plane. They indicated the relation between capillary pressure and degree of saturation. Haverkamp et al. [3] compared the numerical simulation models for one -dimensional infiltration. They reported that the implicit schemes with implicit, or explicit evaluation of the hydraulic conductivity and water capacity functions appear to have the widest range of applicability for predicting water movement in soil with both saturated and nonsaturated regions. Wang Quan-Jiu et al. [4] reported an analytical solution for one-dimensional water infiltration and redistribution in unsaturated soil. Their results showed that the model is convenient and simple to use for predicting soil water movement without evaporation. Nevertheless, a few experimental of large-scale infiltration have been reported by Haim Gvirtzman et al. [5], Kulongoski and Izbicki [6] and Zheng Xiuqing et al. [7].

The excellent reviews concerning problem of heat and mass transport in porous media have been performed by Aoki et al. [8]. Ratanadecho et al. [9–13], Ying Ma et al. [14], Henry and Smith [15], Binning and Celia [16] and Parlange [17].

Although water infiltration processes have been studied actively for several decades, relatively few study reports the problem of heat transfer in granular packed bed coupled with unsaturated flow systematically, especially considering the effects of particle sizes, supplied water flux and supplied water temperature. This work is extended from the work of Aoki et al. [8] and carried out on experimental work for analysis of heat transport and water infiltration in granular pecked bed in several testing conditions. The purpose of this work is to study the influences of the particle

* Corresponding author. Tel.: +66 0 2564 3001 9; fax: +66 0 2564 3010.
E-mail address: ratphadu@engr.tu.ac.th (P. Rattanadecho).

0894-1777/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.expthermflusci.2011.07.003

Nomenclature

s	water saturation of water (-)
ρ_p	density of particle (kg/m^3)
ρ_w	density of water (kg/m^3)
ϕ	porosity (–)
f	supplied water flux (kg/m^2 s)
g	gravity (m^2/s)
k	saturated hydraulic conductivity (m^2)

Subscripts

s	solid
w	water
p	particle

size, supplied water flux and supplied water temperatures on heat transport, water infiltration and infiltration depth during unsaturated flow condition. The result presented here provides a basis for fundamental understanding of heat transport and unsaturated flow in porous media.

2. Experimental apparatus

Fig. 1a and b shows the experimental apparatus for one-dimensional heat transport and water infiltration in granular packed bed. The test column is designed to achieve one-dimensional infiltration flow and heat transport. The test column constructed with inner diameter of 60 mm and 400 mm long column is made of rigid acrylic plastic tubing. The dry porous-ceramic disk at the bottom of the granular packed bed supported the granular particles in the column while allowing a way for air to escape in advance of infiltration depth. Each test column is radially insulated to minimize heat loss through the column walls. A thick plug of insulation is also placed again the ceramic disk of the bottom of column to minimize axial heat loss. To minimize evaporation and convection heat transfer before and during the run, the open end of column is covered with a layer of plastic film. The radial insulation made the columns effectively one-dimensional with respect to heat transfer. Spherical soda lime glass beads with average sizes (d) of 0.15 and 0.4 mm, are used as a sample of granular packed bed. The final assembly thus provided for packing glass beads in the test column with the thermocouples on the axis of the column. The hot water is supplied (supplied water flux, f) from a tank is heated at a certain temperature (T_s) to the top of granular packed bed through a distributor. The hot water supply is controlled by a control valve, where the water flux is calculated from the measured volume used over a period of time. The test column is covered with the insulation in order to reduce heat loss through the ambient. The temperature distributions within test columns are measured with Cu–C thermocouples with diameter of 0.1 mm. These thermocouples are inserted to approximately the center line with 20 mm interval along the vertical axis of test column. The distributions of temperature are recorded by a data logger connected to a computer.

The position of infiltration depth in the packed bed is captured by digital camera relative to a time-base reference as shows in Fig. 2. Fig. 3 shows the experimental apparatus for measuring water saturation. At the end of test run, the granular packed bed is cutout into five sections in small volume of 183 cm^3 in order to measure the water saturation. The water saturation in the non-hygroscopic porous packed bed was defined as the fraction of the volume occupied by water to volume of the pores. This water saturation was obtained by weighing dry and wet mass of the sample. Before the experiment, each section was weighed individually to record its dry mass. The porous packed bed was weighed again at 5 min and 10 min after test run. The water saturation formula can be described in the following form [11]:

$$s = \frac{\rho_p \cdot (1-\phi) \cdot (m_w - m_d)}{\rho_w \cdot \phi \cdot m_d} \quad (1)$$

where s is water saturation, ρ_p is density of particle, ρ_w is density of water, ϕ is porosity, m_w and m_d are wet and dry mass of the sample, respectively.

Initially, the water saturation and the temperature are uniformed within packed bed are 0.06 and 25 °C respectively. The experiments are carried out for the conditions of constant supplied water flux and constant temperature of hot water.

3. Results and Discussion

In this work, the effects of the particle sizes (d) and supplied hot water flux (f) to the temperature distribution, water saturation and infiltration depth will be discussed in details. The experiment is carried in one-dimension assuming that the local thermal equilibrium

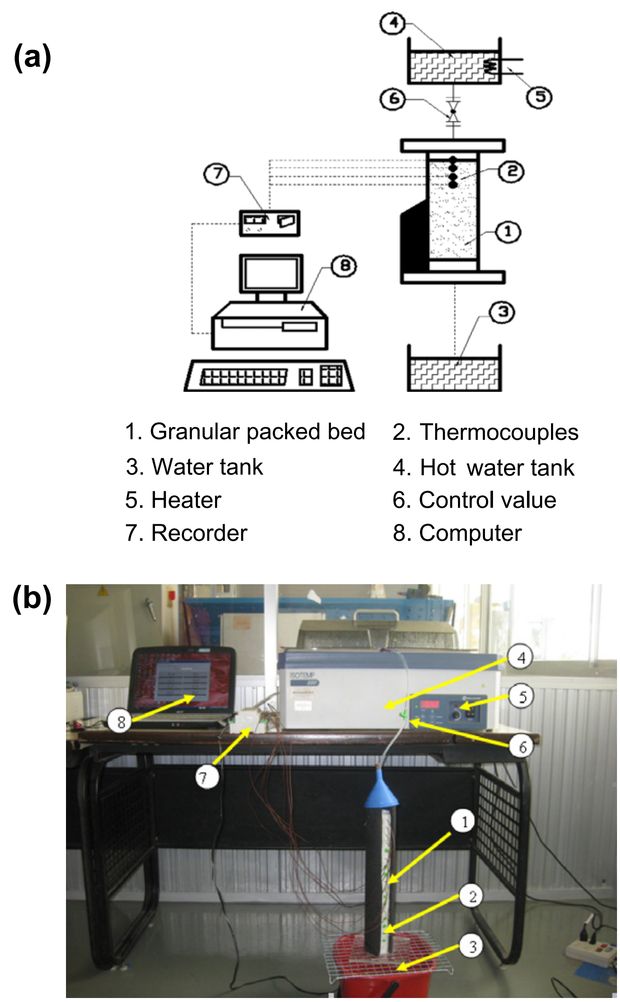

Fig. 1. Experimental apparatus for measuring heat transport and water infiltration in granular packed bed (a) schematics diagram and (b) actual experimental setup.

Fig. 2. Experimental apparatus for measuring infiltration depth of water.

Fig. 3. Experimental apparatus for measuring water saturation in granular packed bed.

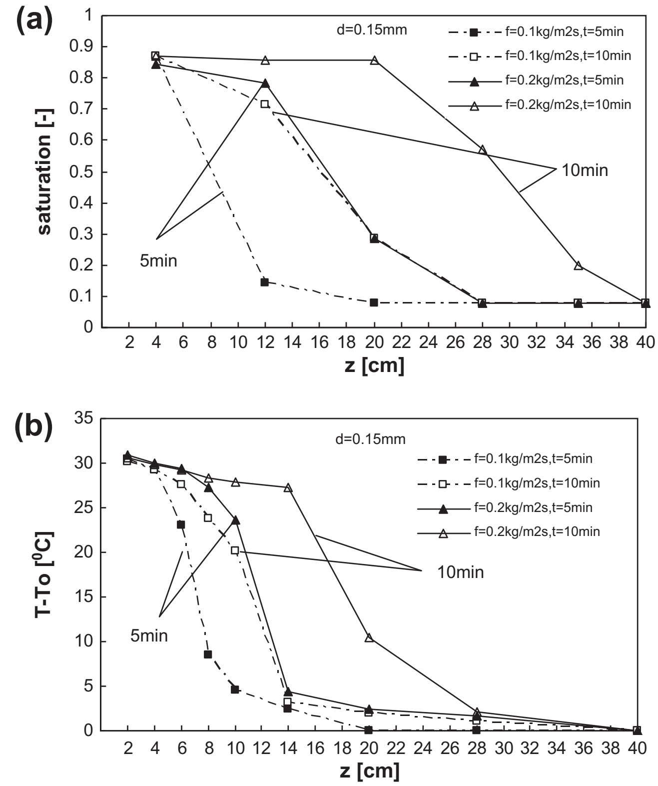

Fig. 4. Distribution of water saturation (a) and temperature profiles (b) with respect to elapsed times as a parameter of supplied water flux. [$d = 0.15$ mm, supplied water temperature, $T_s = 55$ °C].

among water and particles at any specific space. Experimentally, the particle sizes used in this work are 0.15 mm and 0.40 mm in diameter, supplied water fluxes are 0.1 kg/m^2 s and 0.2 kg/m^2 s and supplied water temperatures are 25 °C, 55 °C and 65 °C.

In this work, it is noted that the supplied water flux during unsaturated flow is considered to be lower than the supplied water flux due to gravity (Aoki et al. [8]), namely;

$$f \leqslant g.k \tag{2}$$

where f denotes supplied water flux, g denotes gravity and k denotes saturated hydraulic conductivity (permeability). This expression means that the supplied water always infiltrates into granular packed beds.

Fig. 4 shows the distribution of water saturation and temperature with respect to elapsed times (t, the elapsed time is the time passed from the start of a process to end of the process.) as a parameter of supplied water flux (0.1 kg/m^2 s and 0.2 kg/m^2 s) with the same particle size of 0.15 mm in granular packed bed and the supplied water temperature is 55 °C. It is found that using the higher supplied water flux results in a higher water saturation and forms wider infiltration depth, especially in the direction of gravity. This is because the higher supplied water flux leads to higher matrix potential (capillary pressure) gradient in saturated state resulting in a stronger dynamic of water infiltration. Especially for the case of larger particle size ($d = 0.4$ mm) which will be discussed in Fig. 5. The temperature in the granular packed bed rises due to water infiltration, but the heated layer does not extend as much as the infiltration depth. This means that heat transport hardly occurs in the layer closed by the infiltration depth because the temperature of water infiltration has already dropped due to heat transport upstream.

Fig. 5 shows the influence of particle sizes on the distributions of saturation and temperature with respect to elapsed times under

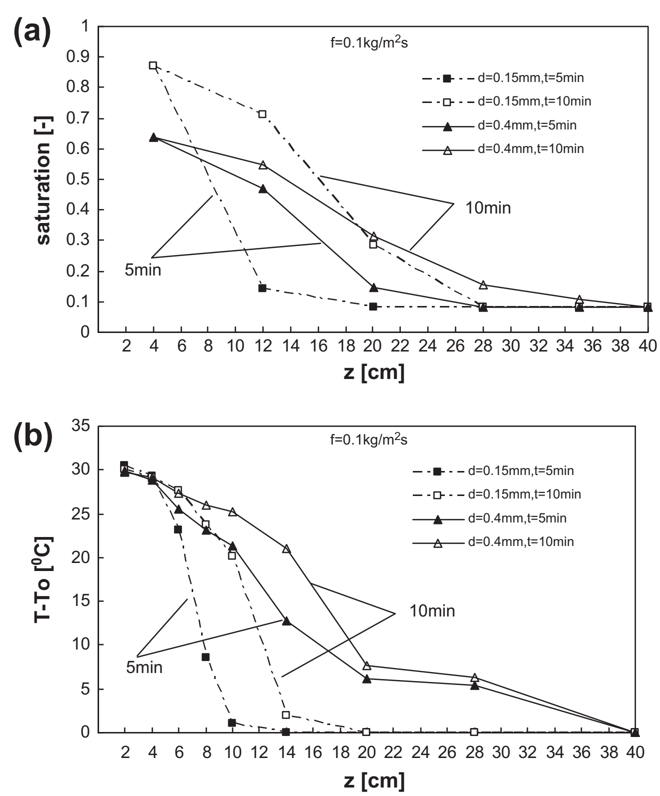

Fig. 5. Distribution of water saturation profiles (a) and temperature distribution (b) with respect to elapsed times as a parameter of particle sizes. [$f = 0.1$ kg/m^2 s, supplied water temperature, $T_s = 55$ °C].

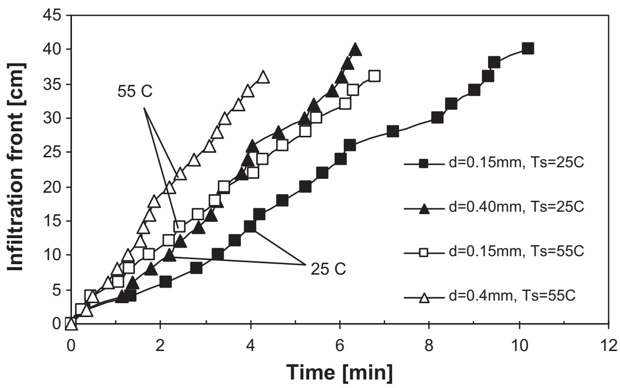

Fig. 6. Infiltration depth with respect to elapsed time as a parameter of particle sizes and supplied water temperatures. [$f = 0.2$ kg/m^2 s].

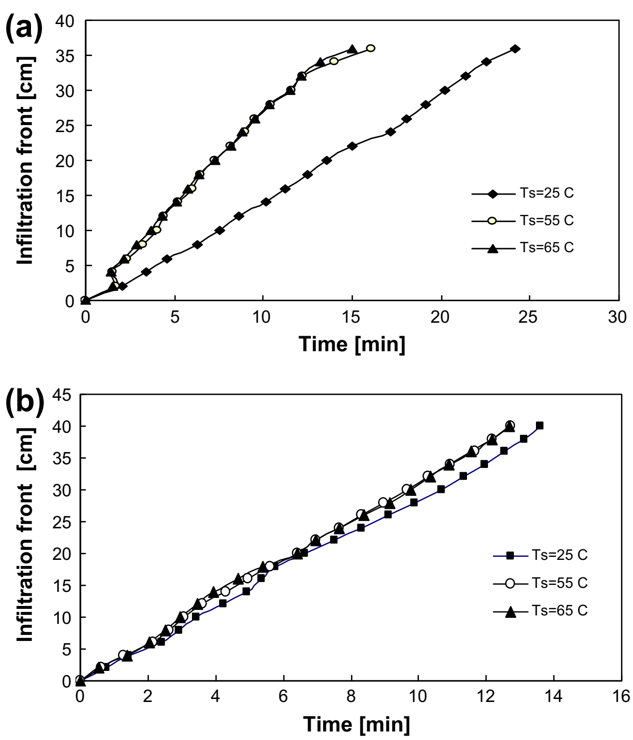

Fig. 7. Infiltration depth with respect to elapsed times as a parameter of supplied water temperatures. [$d = 0.15$ mm] (a) $f = 0.1$ kg/m^2 s and (b) $f = 0.2$ kg/m^2 s.

the same supplied water flux of 0.1 kg/m^2 s and the supplied water temperature of 55 °C with different particle sizes (0.15 mm and 0.4 mm). The results show that a larger particle size leads to faster infiltration rate (infiltration depth) than that of the smaller particle sizes. This is because at the same supplied water flux, the particle size which corresponds to higher capillary gradient, results in a stronger hydraulic conductivity or permeability, as compared to the small particle size. The temperature in granular packed bed rises corresponds to water infiltration. Furthermore, the effect of the fast response is also depended on gravitational force which is stronger effect than the capillary action. Fig. 6 shows the infiltration depth with respect to elapsed times of the packed bed as a parameter of particle sizes (0.15 mm and 0.4 mm) and water supplied temperatures (25 °C and 55 °C) at supplied water flux of 0.2 kg/m^2 s. It is found that a larger particle size in the packed bed corresponds to a faster infiltration rate (infiltration depth) than smaller particle size as similarly explained earlier. The higher water supplied temperatures results in a wider infiltration depth where the reason for explained the phenomena will be performed in the next figure. The effect of the fast response depends on the permeability and the capillarity properties of the particles. Fig. 7 shows the infiltration depth with respect elapsed times as a parameter of supplied water fluxes (0.1 kg/m^2 s and 0.2 kg/m^2 s) and water supplied temperatures (25 °C, 55 °C and 65 °C) at particle size of 0.15 mm. It is found that higher supplied water temperature correspond to a faster infiltration front than lower supplied water temperature, but the results not linearly related to the interference between the heat transport and hydrodynamic characteristics during water infiltration process. These phenomena needs more study for detailed investigating. Also, the higher supplied water flux corresponds to a faster infiltration rate. Nevertheless, not clearly different of infiltration depth have been shown for the case of higher supplied water flux due to the heat transport and hydrodynamic characteristics as explained above. It is evident from the figures that the effect of particle sizes overcomes the effect of supplied water temperatures. This means that the internal phenomena control the simultaneously heat transport and water infiltration in unsaturated porous media for this work.

4. Conclusions

The heat transport and water infiltration in granular packed bed with unsaturated flow is investigated. The following are the conclusions of this work:

1. As comparing the distribution profiles between heated layer and infiltration depth, it is observed that the heated layer does not extend as much as the infiltration depth. This means that heat transport hardly occurs in the layer close to the infiltration depth because the temperature of water infiltrating gradually drops due to heat transport upstream.
2. It is found that the gravity and capillary pressure have clearly exhibited influence on the infiltration and heated layers. Furthermore, the effect of particle size on the discrepancy of temperature distribution as well as heated layers is smaller compared to that of the water saturation layers.
3. The supplied water temperature, supplied water flux and particle size appears to influence on infiltration depth. Additionally, the effect of particle size plays an important role on water infiltration when compared with the effect of supplied water temperature due to the stronger hydrodynamics effect.

In the future, we will be carried out on numerical analysis of the water infiltration coupled with heat transport in porous media in order to compare with the experimental results obtained in this work.

Acknowledgment

This work was supported by the Nation Research University Project of Thailand Office of Higher Education Commission.

References

[1] M. Abriola, F. Pinder, A multiphase approach to the modeling of porous media contamination by organic compounds 1. Equation development, Water Resources Research 21 (1985) 11–18.
[2] F. Stauffer, T. Dracos, Experimental and numerical study of water and solute infiltration in layered porous media, Journal of Hydrology 84 (1986) 9–34.
[3] R. Haverkamp, M. Vauclin, J. Touma, P.J. Wierenga, G. Vanchaud, A comparison of numerical simulation models for one-dimensional infiltration, Soil Science Society of America Journal 41 (1977) 285–294.
[4] Wang Quan-Jiu, R. Horton, Fan Jun, An analytical solution for one-dimensional water infiltration and redistribution in unsaturated soil, International Journal of Pedosphere 19 (2009) 104–110.

[5] Haim. Gvirtzman, Eyal. Shalev, Ofer. Dahan, Yossef H. Hatzor, Large-scale infiltration experiments into unsaturated stratified loess sediment: monitoring and modeling, International Journal of Hydrology 349 (2008) 214–229.
[6] J.T. Kulongoski, J.A. Izbicki, Simulation of fluid heat transport to estimate desert stream infiltration, Ground Water 46 (2008) 462–474.
[7] Zheng Xiuqing, M.W. Van Liew, G.N. Flerchinger, Experimental study of infiltration into a bean stubble field during seasonal freeze-thaw period, Soil Science 166 (2001) 3–10.
[8] K. Aoki, M. Hattori, M. Kitamura, N. Shiraishi, Characteristics of heat transport in porous media with water infiltration, ASME/JSME Thermal Engineering Proceeding 4 (1991) 303–308.
[9] P. Ratanadecho, K. Aoki, M. Akahori, Experimental and numerical study of microwave drying in unsaturated porous material, International Communications in Heat and Mass Transfer 28 (2001) 605–616.
[10] R. Prommas, P. Rattanadecho, D. Cholaseuk, Energy and exergy analyses in drying process of porous media using hot air, International Communications in Heat and Mass Transfer 37 (2010) 372–378.
[11] P. Ratanadecho, K. Aoki, M. Akahori, Influence of irradiation time, particle sizes and initial moisture content during microwave drying of multi-layered capillary porous materials, ASME Journal of Heat Transfer 124 (2002) 151–161.
[12] W. Cha-um, P. Rattanadecho, W. Pakdee, Experimental analysis of microwave heating of dielectric material using a rectangular wave guide (MODE:TE10) (case study: water layer and saturated porous medium), Experimental Thermal and Fluid Science 33 (2009) 472–481.
[13] C. Chaktranond, P. Rattanadecho, Analysis of heat and mass transfer enhancement in porous material subjected to electric fields (effects of particle size and layered arrangement), Experimental Thermal and Fluid Science 34 (2010) 1049–1056.
[14] Ying Ma, Shaoyuan Feng, Dongyuan Su, Guangyao Gao, Zailin Huo, Modeling water infiltration in a large layered soil column with a modified Green-Ampt model and HYDRUS-1D, International Journal of Computer and Electronics in Agriculture 71S (2010) S40–S47.
[15] E.J. Henry, J.E. Smith, Numerical demonstration of surfactant concentration-dependent capillarity and viscosity effects on infiltration from a constant flux line source, International Journal of Hydrology 329 (2006) 63–74.
[16] Philip Binning, Michael A. Celia, Practical implementation of the fractional flow approach to multi-phase flow simulation, International Journal of Advances in Water Resources 22 (1999) 461–478.
[17] J.Y. Parlange, Theory of water movement in soils: one-dimensional infiltration, Soil Science 111 (1972) 170–174.