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

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A B S T R A C T

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.

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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], Kulongsoski and Izibicki [6] and Zheng Xiuxing 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 packed bed in several testing conditions. The purpose of this work is to study the influences of the particle

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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-hygrosopic 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 \([11]\):

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

where \(s\) is water saturation, \(\rho_p\) is density of particle, \(\rho_w\) is density of water, \(\phi\) 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

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>(s)</td>
<td>water saturation of water (-)</td>
</tr>
<tr>
<td>(\rho_p)</td>
<td>density of particle (kg/m(^3))</td>
</tr>
<tr>
<td>(\rho_w)</td>
<td>density of water (kg/m(^3))</td>
</tr>
<tr>
<td>(\phi)</td>
<td>porosity (-)</td>
</tr>
<tr>
<td>(f)</td>
<td>supplied water flux (kg/m(^2) s)</td>
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<tr>
<td>(g)</td>
<td>gravity (m(^2)/s)</td>
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<td>(k)</td>
<td>saturated hydraulic conductivity (m(^2))</td>
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Subscripts

<table>
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<tr>
<th>Subscript</th>
<th>Description</th>
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<tr>
<td>s</td>
<td>solid</td>
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<td>w</td>
<td>water</td>
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<td>p</td>
<td>particle</td>
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Fig. 1. Experimental apparatus for measuring heat transport and water infiltration in granular packed bed (a) schematics diagram and (b) actual experimental setup.
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/m² s and 0.2 kg/m² 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:

\[ f < g \cdot k \]  

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/m² s and 0.2 kg/m² 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. 2. Experimental apparatus for measuring infiltration depth of water.](image)

![Fig. 3. Experimental apparatus for measuring water saturation in granular packed bed.](image)

![Fig. 4. Distribution of water saturation (a) and temperature profiles (b) with respect to elapsed times as a parameter of supplied water flux. \([d = 0.15 \text{ mm}, \text{ supplied water temperature}, T_s = 55 \degree \text{C}]\).](image)

![Fig. 5. Distribution of water saturation profiles (a) and temperature distribution (b) with respect to elapsed times as a parameter of particle sizes. \([f = 0.1 \text{ kg/m}^2 \text{s}, \text{ supplied water temperature}, T_s = 55 \degree \text{C}]\).](image)
than smaller particle size as similarly explained earlier. The higher bed corresponds to a faster infiltration rate (infiltration depth) than that of the smaller particle size. The temperature in granular packed bed rises corresponds to water infiltration. Furthermore, the effect of supplied water 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/m² s and 0.2 kg/m² 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.

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References


