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Original research article

Experimental Study of Heat Transfer and Water Infiltration in Two-Layered Granular Packed Bed

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ABSTRACT

The characteristics of heat transfer and water infiltration by hot water into a two-layered two-dimensional granular packed bed have been investigated experimentally. This study aims to understand the influences of the layered configuration of the granular packed bed, supplied water temperature, and supplied water flux on the water infiltration and heat transport in the two-layered granular packed bed. The study illustrated the dynamics of heat transfer and water infiltration in various testing cases. The results showed that the layered configuration of the granular packed bed, supplied water temperature, and supplied water flux have significant effects on the water infiltration and heating pattern of the packed bed. In the case of smaller particles on top (FC-bed), the infiltration front tends to expand in the lateral direction faster than the downward direction. The higher supplied water temperature results in a deeper and wider infiltration. Furthermore, the heating zone is found to be moving a little slower than infiltration front propagation. The findings can be used as basic information for research on other purposes such as heat and water movement in the ground.

Keywords: Granular packed bed; Heat transfer; Temperature distribution; Water infiltration

1. Introduction

The knowledge of the water infiltration process in porous media is important for many fields such as hydrology, soil science, agriculture, civil engineering, and chemical engineering. Infiltration of water in dry porous media is subject to various gravity-driven mass-transport processes.

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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.

Many researchers have carried out research on water infiltration in porous media both experimentally and numerically up to date. Hammecker et al. [1] took a complete set of measurements at various scales and with different techniques and showed that water infiltration into soil is governed by the presence of air trapped between two wetting fronts, namely, irrigation in the upper part and the water table at the lower limit. Gvirtzman et al. [2] presented two large-scale field experiments conducted to track water flow through unsaturated stratified loss deposits. In the experiments, a trench was flooded with water, and water infiltration was allowed unit full saturation of the sediment column. The processes were also simulated using a two-dimensional numerical code that solves the flow equation. The results indicated that above-hydrostatic pressure is developed within intermediate saturated layers, enhancing wetting front propagation. Ma et al. [3] presented a five-layered soil column infiltration experiment to assess the validity of the proposed updated Green-Ampt model against the standard Green-Ampt model. The fitting of experimental data showed that the modified Green-Ampt model can be used as an effective and practical method to estimate water infiltration in layered soils, and the introduced saturation coefficient reflects the effect of air entrapment on water infiltration. Ayu et al. [4] measured the infiltration rate of various types of soil in dryland areas using the double-ring infiltrometer. The data analysis revealed that soil properties affecting infiltration rate in the research locations are sand and clay percentages, soil moisture content, bulk density, particle density, soil organic matter, and soil porosity. Langston and Kennedy [5] developed a numerical model to test spectroscopic parameters related to the packing behavior of relatively large, near-spherical NaCl beads and mixtures of beads of various sizes. The excellent reviews concerning the flow of water in porous media with saturation overshoot have been performed by Xiong [6]. Representative works, for related numerical problems of unsaturated flow under infiltration conditions for different applications, include Henry and Smith [7], Romano et al. [8], Corradini et al. [9], Gomez et al. [10], and Sayah et al. [11].

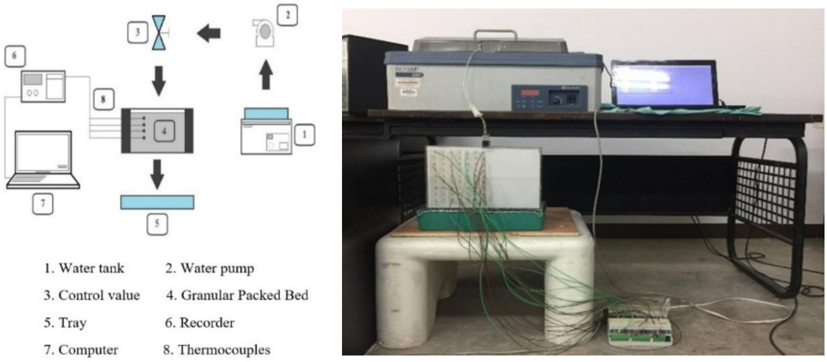
The inclusion of heat transfer into the infiltration process was also considered. Understanding heat transfer in a granular packed bed or porous media with water infiltration due to capillary action is important in a variety of soil science and chemical engineering applications, such as soil temperature regulation, geothermal energy recovery, thermal energy storage, and various chemical reactors. Up to the present time, the related applications of heat transfer and water infiltration in porous media have been investigated both experimentally and numerically. In the last decade, only a few experiments have been reported. Bandai et al. [12] experimented to investigate the effect of particle size on thermal and solute dispersion in saturated porous media. The study showed that the thermal dispersion coefficient was influenced by particle size. A few numerical investigations have also been carried out by some researchers. Boonwan et al. [13] developed a mathematical model to predict soil temperature for the growth of chrysanthemum sprouts. The result has been compared with an experimental study. It was found that the soil temperatures obtained from the model were slightly higher than the measure values. D.Gobin et al. [14] developed a macroscopic model of casting a metal foam solidification of liquid metal in porous media and infiltration. The developed model was used to determine the influence of the operating conditions on the penetration depth and on the solidification time in a simplified geometry before using this local information in a macroscopic homogenized model.

Our research group has also been studying for a coupled heat transfer with water infiltration in the porous medium [15-16]. Suttisong and Rattanadecho [15] conducted an experimental investigation of heat transport and water infiltration in a vertical granular packed bed column. The results showed that the granular packed bed with a larger particle size results in a faster infiltration rate and forms a wider infiltration depth. Rattanadecho et al. [16] carried out a one-dimensional model assuming the local thermal equilibrium between water in a vertical granular packed bed column. The calculated temperature distribution, water saturation, and infiltration depth were compared with the experimental results. It was found that a greater supplied water flux corresponds to temperature along a granular packed bed for each time increment and higher water saturation. The numerical results closely match the experimental results.

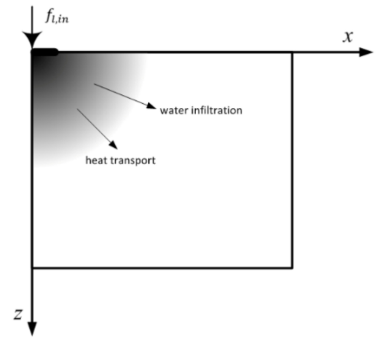
Although the process of water infiltration has been studied for many years, there are still very few studies that report the problem of heat transfer coupled with the unsaturated flow in two-dimensional granular packed bed systematically. Especially the work considering the effect of particle sizes on transport phenomena with capturing infiltration depth in the two-dimensional packed bed has not been investigated before. This work is substantially extended from our previous work [15], in which we propose to consider the effect of layered configuration in the analysis. The purpose of this paper is to clarify the characteristics of heat transfer and water infiltration into a two-layered two-dimensional granular packed bed. The effects of layered configuration, supplied water temperature and supplied water flux on heat transport and water infiltration are investigated experimentally. The obtained results provide a basis for a fundamental understanding of heat transfer and water infiltration in granular packed beds.

2. Experimental Apparatus

Fig. 1 shows the experimental apparatus for a two-layered two-dimensional rectangular granular packed-bed. The rectangular test column is made of rigid acrylic plastic with inside dimensions of 30 cm in length, 20 cm in height, and 5 cm in width. The test cell is surrounded by 6 cm thick Styrofoam to reduce heat loss and moisture condensation at the wall. The test column is filled with uniform size (d) spherical glass beads with a diameter of 0.05 mm (F-Bed), and 0.15 mm (C-Bed). Glass beads are packed in the test column with the thermocouples on the column's axis in the final setup. The hot water is supplied (supplied water flux, f) from a tank, that is heated to a specific temperature (T_s), to the top of the granular packed bed through a distributor. A control valve controlled the hot water supply where the water flux is calculated from the measured volume used over a period of time. Measurement of temperature distributions inside the test column is accomplished using thermocouples. A data logger connected to a computer records all 24 locations of the test column's thermocouples.



(a)



(b)

Fig. 1. Schematic diagram of the experiment set-up: (a) experimental apparatus for two-layered two-dimensional rectangular granular packed-bed. (b) a symmetrical model represents the heat transfer and water infiltration within the two-dimensional granular packed bed.

3. Results and Discussion

3.1 Parametric study

In this study, the dynamics of heat transfer and water infiltration are described for differing circumstances. The study employs particle sizes of 0.05mm (fine particles) and 0.15mm (coarse particles) in diameter. We consider two porous packed bed systems, FC-bed (fine bed attached over coarse bed) and CF-bed (coarse bed attached over fine bed). The result focuses attention on the comparison of cases in arranging a large particle layer on top (CF-bed) and a small particle layer on top (FC-bed). The influences of three parameters, namely, the layer configuration (CF-Bed and FC Bed), the supplied water temperature (25 °C, 45 °C, and 55 °C), and the supplied water flux (f = 0.15 kg/m^{2}s and f = 0.20 kg/m^{2}s) have been systematically investigated. From the parametric study, we observe the effects associated with each factor and analyze their contributions to the water infiltration, the infiltration front, the temperature distribution, and the temperature increase.

3.2 Effect of layer configuration

Figs. 2 and 6 show the effect of layer configuration on water infiltration in the granular packed beds at the supplied water fluxes of 0.15 kg/m^{2}s and 0.20 kg/m^{2}s, respectively. As shown in the results, the water permeability in the CF-bed is faster than the water permeability in the FC-bed. This is due to the large particle layer (coarse particle) being placed in the upper part of the CF-bed. In the upper part of the CF bed, the water permeability is relatively high due to a little water retention of large porous particles, causing the water to infiltrate downward quickly and spread only a small distance in the lateral direction. When the small particle layer (fine particle) is placed below, high capillary pressure results in slowing the infiltration downward and a wider spread of the water distribution over the entire region. As for the FC-bed particles, the small particle layer placed in the upper part of the FC-bed, which contains very small continuous pores, has low permeability and transmits water very slowly. The water slowly transmits through the small particles on the upper part and temporarily stops further infiltration when it reaches the boundary between the upper and lower porous layers due to the effect of the high capillary pressure in the small particle layer. As a result, the water spreads in a lateral direction of the small particles packed bed on the top layer as shown in Figs. 6 and 7. When the capillary pressure drops below the liquid pressure, the water will continue to fill the pores of the large particle layer below.

Figs. 3 and 7 show the effect of layer configuration on temperature distribution in the granular packed beds at the supplied water fluxes of 0.15 kg/m^{2}s and 0.20 kg/m^{2}s, respectively. As seen, the FC-bed has a wider heat distribution than the CF-bed in the top layer, which corresponds to the water spread across the entire area of the packed bed. This is because the top layer with smaller particles has a large water retention capacity, allowing the water to infiltrate and move slowly. Therefore, the heat has a longer time to be accumulated in the pore space of the small particles on the top layer before it is transmitted down to the bottom layer. Compared to the CF-bed, it has a smaller heat distribution but the heated region penetrates faster and deeper. This is due to the lower water retention capacity and high permeability of the large particle layer placed on top of the CF-bed that allows the water to pass through it easily. Besides it is observed that the heating zone is moving a little slower than infiltration front propagation. This is because the high-temperature gradient during the early stage of infiltration causes heat dissipation into the environment so that the heat loss that occurs along the way leads to a drop in temperature in the deep region beneath the infiltration distributor.

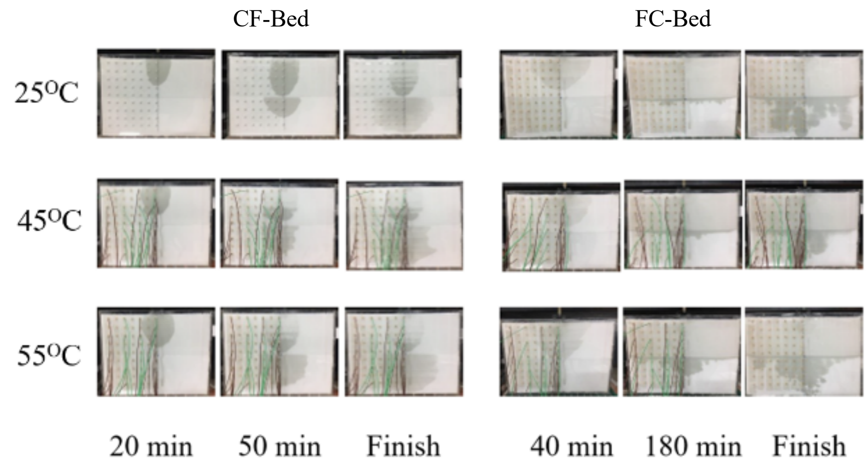


Fig. 2. Experimental results of water infiltration in CF-bed and FC-bed at various times (supplied water flux f = 0.15 kg/m^{2}s).

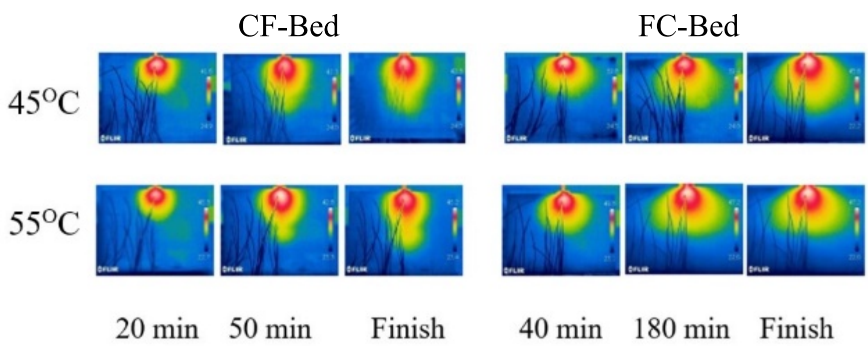


Fig. 3. Experimental results of temperature distribution in CF-bed and FC-bed at various times (supplied water flux f = 0.15 kg/m^{2}s).

3.3 Effect of supplied water temperature

The supplied water temperature also affects water infiltration and heat transfer in the two-layered granular packed bed. Figs. 4 and 8 show the effect of supplied water temperature on infiltration front in the granular packed beds at the supplied water fluxes of 0.15 kg/m^{2}s and 0.20 kg/m^{2}s, respectively. As we noted earlier, the FC-bed had poor permeability compared with CF-bed. Moreover, according to the results in Figs. 4 and 8, when increasing the supplied water temperature, the infiltration rate will be faster as a result of the capillary pressure reduction at the wetting front. This is because water infiltration in the granular packed bed takes place as a result of gravity and a capillary pressure gradient. The capillary pressure gradient governs liquid phase migration, which is also heavily influenced by temperature and corresponded to the surface tension.

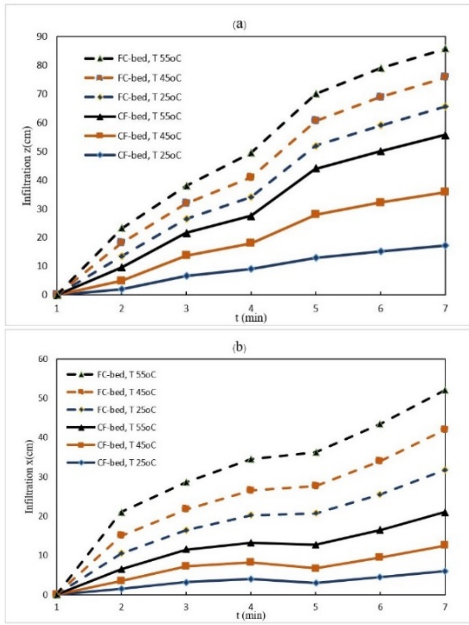


Fig. 4 Comparison of infiltration front in CF-bed and FC-bed at different supplied water temperatures: (a) infiltration front in z-axis, (b) infiltration front in x-axis, (supplied water flux f = 0.15 kg/m^{2}s).

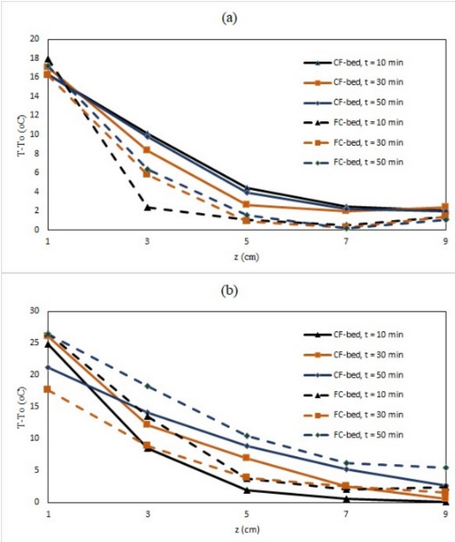


Fig. 5. Comparison of temperature increase in CF-Bed and FC-Bed at the supplied water flux f = 0.15 kg/m^{2}s: (a) supplied water temperature 45^{o}C, (b) supplied water temperature 55^{o}C.

3.4 Effect of supplied water flux

The supplied water flux also plays an important role in water infiltration and heat transfer in the two-layered granular packed bed. Figs. 2 and 6 show infiltration in the granular packed beds at the supplied water fluxes of 0.15 kg/m^{2}s and 0.20 kg/m^{2}s, respectively. It is found that the higher supplied water flux results in a faster infiltration rate and forms a wider infiltration layer. Fig. 10 shows the effect of supplied water flux on infiltration front in the granular packed beds. As we know, water infiltration takes place as a result of gravity and a capillary back-pressure. For the same layer configuration, a higher supplied water flux allows faster infiltration front movement, especially in the direction of gravity due to the gravitational force exerted downward in the z-direction as shown in Fig. 10. Moreover, a greater supplied water flux corresponds to higher water saturation. The higher water saturation leads to lower capillary back-pressure which is much less than the gravitational effect resulting in an increase in water infiltration capacity. As shown on the graph in Fig. 10, the expansions of water infiltration front in both x and z-directions are found because capillary pressure also exerts a significant effect on the water propagation behavior inside the packed bed compared to the gravity. However, in the case of smaller particles on top (FC-bed), the infiltration front tends to expand in the lateral direction (x-direction) faster than the CF-bed. This is because the capillary pressure becomes stronger than the gravity force which controls the fluids distribution in the top part of the packed bed.

Figs. 5 and 9 show the temperature increases in the granular packed beds at the supplied water fluxes of 0.15 kg/m^{2}s and 0.20 kg/m^{2}s, respectively. As a result of water infiltration, there is an increase recorded in the granular packed bed temperature. It can be observed that for the same packed bed configuration, the temperature increases present similar patterns along the z-axis for all cases. Comparison between the temperature increases in the packed beds while exposed to the supplied water fluxes of 0.15 kg/m^{2}s (Fig.5) and 0.20 kg/m^{2}s (Fig.9). It can be seen that in the case of higher supplied water flux, the temperature increments are propagated deeper and faster in the direction of gravity along the z-direction corresponding to the infiltration front propagation. This is because when increasing the supplied water flux, the gravity effect will overtake the influence of capillary pressure, allowing the infiltration front and heated layer to expand widely in the z-direction.

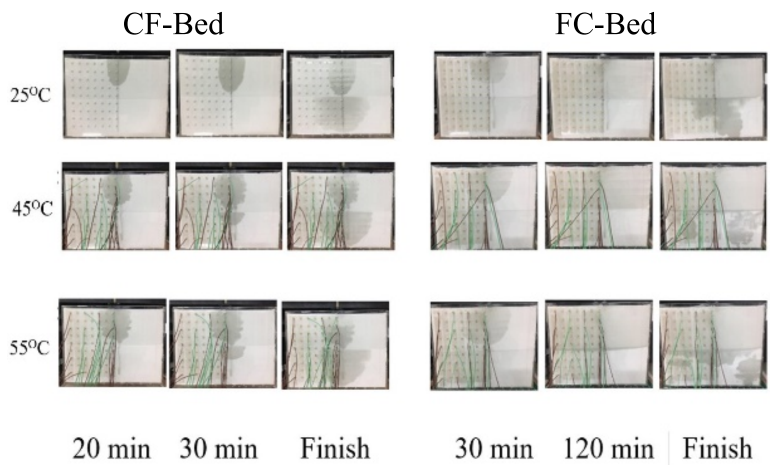


Fig. 6. Experimental results of water infiltration in CF-bed and FC-bed at various times (supplied water flux f = 0.20 kg/m^{2}s).

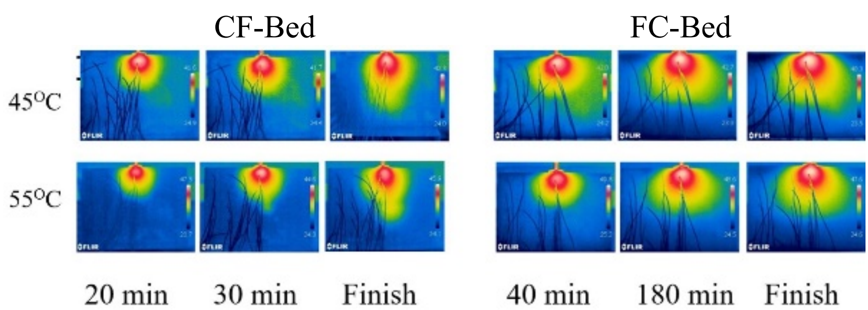


Fig. 7. Experimental results of temperature distribution in CF-bed and FC-bed at various times (supplied water flux f = 0.20 kg/m^{2}s).

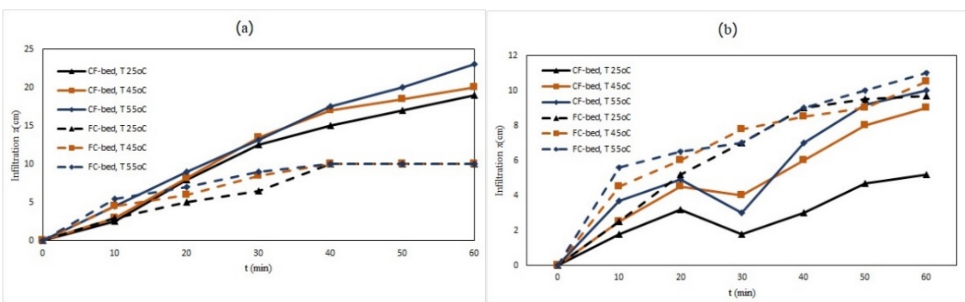


Fig. 8. Comparison of infiltration front in CF-bed and FC-bed at different supplied water temperatures: (a) infiltration front in *z*-axis, (b) infiltration front in *x*-axis (supplied water flux f = 0.20 kg/m^{2}s).

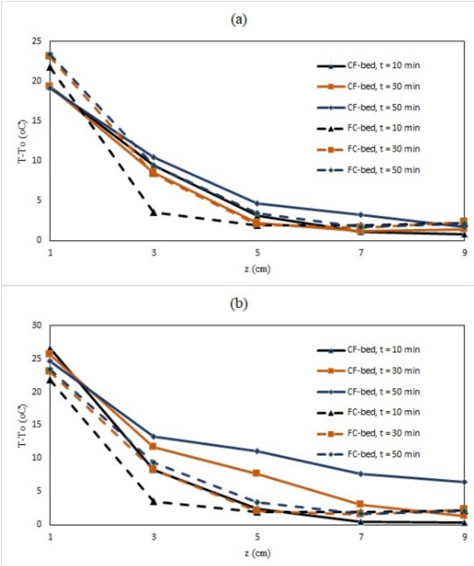
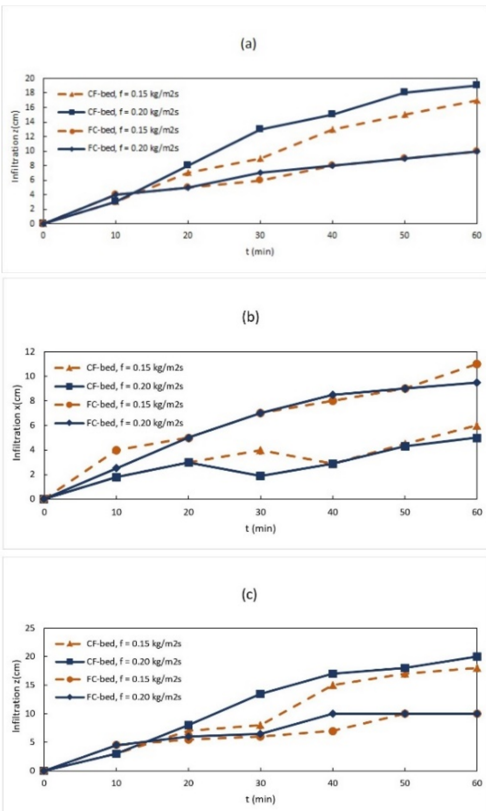


Fig. 9. Comparison of temperature increase in CF-Bed and FC-Bed at the supplied water flux f = 0.20 kg/m^{2}s: (a) supplied water temperature 45°C, (b) supplied water temperature 55°C.



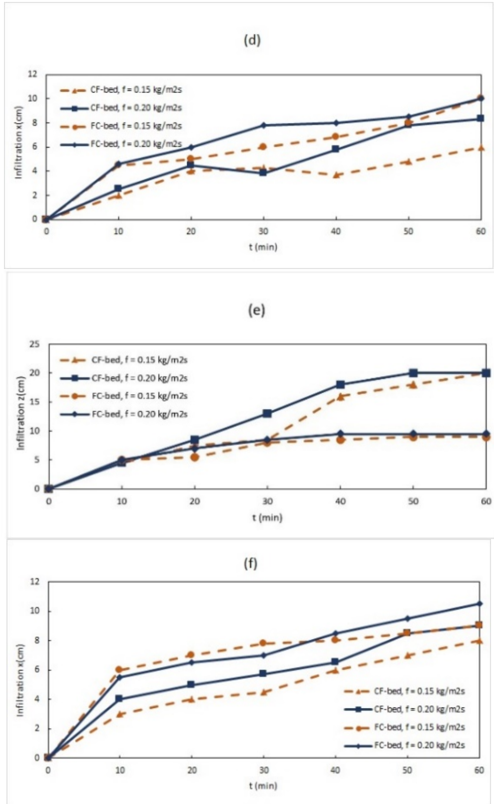


Fig. 10. Comparison of infiltration front at the supplied water fluxes f = 0.15 kg/m^{2}s and f =0.2 kg/m^{2}s in FC-Bed and CF-Bed:
(a) infiltration front in *x*-axis at supplied water temperature 25°C,
(b) infiltration front in *z*-axis at supplied water temperature 25°C,
(c) infiltration front in *x*-axis at supplied water temperature 45°C,
(d) infiltration front in *z*-axis at supplied water temperature 45°C,
(e) infiltration front in *x*-axis at supplied water temperature 55°C,
(f) infiltration front in *z*-axis at supplied water temperature 55°C.

4. Conclusion

The characteristics of heat transfer and water infiltration by hot water into a two-layered two-dimensional granular packed bed have been investigated experimentally. The study illustrated the dynamics of heat transfer and water infiltration in various testing cases. The findings explore the effects associated with each factor and analyze their contributions to the water infiltration, the infiltration front, the temperature distribution, and the temperature increase. The key findings can be summarized as follows:

1) The CF-bed has a fast downward infiltration rate compared with the FC-bed because of a little water retention of large particle layer placed in the upper part of the CF-bed. In the case of smaller particles on top (FC-bed), the infiltration front tends to expand in the lateral direction faster than the downward direction. This is because the capillary pressure of fine particles exerts a significant effect on the water propagation behavior inside the packed bed compared to the gravitational force. Moreover, the water temporarily stops further infiltration when it reaches the boundary between the upper and lower porous layers due to the effect of the high capillary pressure in the small particle layer.

2) When increasing the supplied water temperature, the infiltration rate will be faster as a result of the capillary pressure head reduction at the wetting front. The heating zone is moving a little slower than infiltration front propagation because the heat loss that occurs along the way leads to a temperature drop at the infiltration front position.

3) Increasing the supplied water flux results in a faster infiltration front moving especially in the direction of gravity because of the gravitational force exerted downward in the z-direction. In the case of higher supplied water flux, the temperature increments are also being propagated deeper and faster in the downward direction corresponding to the infiltration front propagation.

A better understanding of the influences that affect the water infiltration and heat transport in the two-layered granular packed bed has been identified. Based on the results, it can be concluded that the layered configuration of the granular packed bed, supplied water temperature, and supplied water flux have significant effects on the water infiltration and heating pattern of the packed bed. The obtained results provide a basis for a fundamental understanding of heat transfer and water infiltration in granular packed beds. The findings can be used as basic information for research on other purposes such as heat and water movement in the ground.

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References

[1] Hammecker, Antonino ACD, Maeght JL, Boivin P. Experimental and numerical study of water flow in soil under irrigation in northern Senegal: evidence of air entrapment. European Journal of Soil Science 2003; 54:491-503.

[2] Gvirtzman, H., Shalev E, Dahan O, Hatzord YH. Large-scale infiltration experiments into unsaturated stratified loess sediments: Monitoring and modeling. Journal of Hydrology 2008; 349:214-29.

[3] Ma, Y., Feng S, Su D, Gao G, Huo Z. Modeling water infiltration in a large

layered soil column with a modified Green-Ampt model and HYDRUS-1D. Computers and Electronics in Agriculture. 2010; 71S:S40-7.

[4] Ieke Wulan Ayu, S.P.a.S. Assessment of Infiltration Rate under Different Drylands Types in Unter-Iwes Subdistrict Sumbawa Besar, Indonesia. Journal of Natural Sciences Research. 2013; 3(10): 71-7.

[5] Langston, P. and A.R. Kennedy. Discrete element modelling of the packing of spheres and its application to the structure of porous metals made by infiltration of packed beds of NaCl beads. Powder Technology. 2014; 268:210-8.

[6] Xiong, Y. Flow of water in porous media with saturation overshoot: A review. Journal of Hydrology. 2014; 510:353-62.

[7] Henry, E.J. and J.E. Smith. Numerical demonstration of surfactant concentration-dependent capillarity and viscosity effects on infiltration from a constant flux line source. Journal of Hydrology. 2006; 329:63-74.

[8] Romano, N., B. Brunone, and A. Santini. Numerical analysis of one-dimensional unsaturated flow in layered soils. Advances in Water Resources. 1998; 21:315-24.

[9] Corradini, C., F. Melone, and R.E. Smith. Modeling local infiltration for a two-layered soil under complex rainfall patterns. Journal of Hydrology. 2000; 237:58-73.

[10] Gomez, H., L. Cueto-Felgueroso, and R. Juanes. Three-dimensional simulation of unstable gravity-driven infiltration of water into a porous medium. Journal of Computational Physics. 2013; 238:217-39.

[11] Sayah, B., M. Gil-Rodriguez, and L. Juana. Development of one-dimensional solutions for water infiltration. Analysis and parameters estimation. Journal of Hydrology. 2016; 535:226-34.

[12] Bandai T, Hamamoto S, Rau G, Komatsu T, Nishimura T. The effect of particle size on thermal and solute dispersion in saturated porous media. International Journal of Thermal Sciences. 2017; 122:74-84.

[13] Boonwan C, Yamfang M, Thepa S, Sukchana T, Pruengam P, Pairintra R, Kuptasa M. Development of a mathematical model to predict soil temperature for the growth of chrysanthemum sprouts. Research Journal Rajamangala University of Technology Thanyaburi. 2020; 19:74-85.

[14] Moussa N, Gobin D, Duval H, Goyeau B. Infiltration of a porous matrix by a solidifying liquid metal: A local model, International Journal of Thermal Sciences. 2017; 120:481-90.

[15] Suttisong, S. and P. Rattanadecho. 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. Experimental Thermal and Fluid Science. 2011; 35:1530-4.

[16] Rattanadecho, P., S. Suttisong, and T. Somtawin. The Numerical and Experimental Analysis of Heat Transport and Water Infiltration in a Granular Packed Bed Due to Supplied Hot Water. Numerical Heat Transfer. 2014; Part A: Applications. 65(10):1007-22.