Characteristic lengths affecting evaporation from porous media: The roles of pore size distribution, gravity and wettability

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Introduction

• The drying of porous media affects land-atmosphere water exchange and surface energy balance, and is important for many biological and engineering applications.

• Evaporation rate depends on external boundary conditions and on the textural and transport properties of porous media.

• Drying rate from porous media may exhibit an abrupt change into much lower value and consequently consuming more energy.
Open questions

- Prediction of drying rate remains an open question due to dependency on atmospheric demand (temperature, humidity and air flow velocity), complexity of pore spaces and interplay between different forces.

- Abrupt transitions in evaporation rates are not fully understood.

- Unknown roles of heterogeneity and pore size distribution in drying rates and liquid phase distribution.

Yiotis et al. (2004)
Objectives

- Quantify effects of pore size distribution & external conditions on drying behavior of porous media
- Characterize effects of textural contrasts on evaporation from porous media
- To determine dominant mechanisms supplying and controlling drying rate
- To determine liquid phase distribution during drying of porous media
Observations in uniform sands: transition in evaporation rates

- Columns of different lengths packed with sand (~0.3-0.9mm) - initially saturated; constant B.C.
- Abrupt transition from stage 1 (high) to stage 2 (low) evaporation rate at similar mass loss irrespective of column length
- Hypothesis - transition marks end of mass flow supporting externally-imposed evaporation rate (stage 1) and transition to vapor diffusion (stage 2)
- What determines drying front depth at transition?
Evaporation in uniform sands – particle size effects

- Clues - (1) transition occurs at the same drying front depth for a given medium; (2) transition is delayed for finer-textured media
Characteristic lengths & evaporative mass flows

- Evidence - _stage 1_ is sustained by liquid flow across a characteristic length spanned by hydraulically connected _pore size distribution_ (linking drying front with evaporating surface)

- A simple model for capillary interactions and drying front displacement during evaporation uses a _pair of hydraulically interacting capillaries_ (Krischer, 1956)

Hydraulic coupling and capillary-driven liquid flow to evaporating surfaces (while drying front recedes into the medium) are key to sustaining constant rate evaporation
A bundle of interacting capillaries model - (Krischer, 1956)

- Key evaporation interactions could be described by a pair of hydraulically interacting capillaries (Krischer, 1956)
- These interactions highlight the key mechanism by which a constant evaporation rate is maintained!

\[ L_c = \frac{2\sigma}{\rho g} \left( \frac{1}{r_2} - \frac{1}{r_1} \right) \]
Pore size distribution & characteristic length

- Drying front depth at transition to stage 2 varies with medium

The characteristic length is determined by hydraulically connected pore size distribution (deduced from SWC)

\[ L_c = \frac{2\sigma}{\rho g} \left( \frac{1}{r_{\text{min}}} - \frac{1}{r_{\text{max}}} \right) \]
Drying of layered sand columns

• To apply the concept of characteristic length in more general case, drying experiment with glass column packed with layered sand under initially saturated condition have been conducted.

Fine sand 0.1-0.5 mm
Coarse sand 0.3-0.9 mm
Changes in evaporation rates

- Abrupt transition from stage 1 to stage 2 of drying rate was sensitive to the position of coarse layer. The closer position of coarse layer to surface, the sooner transition
Liquid flow toward surface

- The concentration of blue color at surface increased gradually during experiment showing evaporation of water at surface!

- Initial rate of drying occurs at potential atmospheric demand irrespective of layering sequence.
Predictable drying front depth for layered media

- Transition occurs at a predictable drying front depth for a given sequence and position of layered media reflecting the most limiting characteristic length in the sequence
Neutron radiography: Detailed Drying dynamics

- Neutron attenuation used to analyze the liquid phase distribution and morphology of the drying front during drying.
- The attenuation of neutrons was measured every 5 minutes.
- Changes in total mass loss, relative humidity, temperature, and wind speed were recorded digitally.

![Graph showing mass loss by neutron attenuation vs mass loss by balance (g)](graph.png)
Neutron radiography: Image analysis

- The grey level image has to be segmented into black and white image to analyze dynamics of drying front.

- Black and white colors correspond to the water and air phases, respectively.
Dynamics of drying front in HI sand
Dynamics of drying front

- Hydrophilic and hydrophobic sand used for drying experiments to analyze the impact of capillary forces on drying rate as well dynamics of drying front
- Wettability imposes limitation on dynamics of drying front.
- Pinning and unpinning of drying front is more visible within HI sand due to stronger capillary forces.
Wettability

- An important issue solved by neutron radiography was delineating near surface water content affected by Wettability.

- Lower near surface water content in HO sand may be the main reason in lowering the rate of liquid flow toward surface.
Liquid flow vs. Vapor diffusion: effects on evaporation

- Measured drying rate was much higher than estimated based on vapor diffusion from drying front to surface indicating dominant role of liquid flow
What next?

- Effect of partial wettability on characteristic length
- Role of gravity
- Evaporation-condensation mechanism
- Vapor diffusion from isolated clusters left behind drying front could be a mechanism to enhance drying rate
- In very fine textured media, viscous dissipation may be important defining a viscous characteristic length.
Summary and conclusions

- First stage of drying is affected by continuous liquid paths spreading within porous media sustaining hydraulic connection between drying front and evaporating surface.
- Diffusive fluxes cannot explain drying rate in the first stage.
- Characteristic length could be deduced from capillary pressure-saturation curve to predict transition from stage 1 to stage 2.
- Drying is an atmospheric controlled process in the first stage, disrespective to the structure of porous medium.
- Neutron radiography measurement established existence of hydraulic connection between drying front and evaporating surface and is a powerful technique to deduce the dynamics and morphology of drying front as well temporal and spatial water content distribution.
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Temperature and relative humidity

- Temperature and relative humidity was nearly constant and equal in drying experiments on HI and HO sand.
Water content distribution

- Results showed average water content distribution was not affected by evaporation rates, but by wettability of sand.
- In HI sand, water content was not increased monotonically from surface due to formation of isolated water cluster within sand preserved by capillary forces for a long time, whereas in HO sand it increased monotonically from surface.
Drying rate and hydraulic conductivity

- Much higher hydraulic conductivity than measured drying rate indicated no hydraulic limitation on mass flow during the considered period

- Alternative explanation for falling drying rate is related to the coupling between external viscous boundary layer with decreasing surface water content