Proceedings of the 3rd Thermal and Fluid Engineering Summer Conference, TFESC
March 4-7, 2018, Ft. Lauderdale, FL, USA

TFESC-20972

EVAPORATION FROM POROUS MEDIA: SINGLE HYDROPHOBIC AND HYDROPHILIC PORES

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Abstract

Worldwide, agriculture is responsible for two-thirds of water withdrawals because many productive, food-producing areas lack sufficient rainfall to grow crops without irrigation. In much of the Great Plains, the Ogallala Aquifer is the primary water source for food production, and diminishing water levels require improvements in sustainable agriculture. Reductions in soil evaporation rates will reduce irrigation demands and overall water consumption for crop production, thereby conserving water in areas such as the Ogallala Aquifer. In this study, evaporation of water is studied in a single pore comprised of three 2.38-mm diameter beads to simulate a soil pore. Evaporation times and high-speed imaging were recorded for hydrophilic (i.e., glass) and hydrophobic (i.e., Teflon) beads. Experiments were conducted with moist air at approximately 22.5 °C and approximately 60% RH. Water evaporated faster from the hydrophilic beads; contact line and angle dynamics were documented for hydrophobic and hydrophilic cases. The study found that for droplets on hydrophobic beads the evaporation times were on average 55 minutes and contact area decreased with evaporation. In contrast, water droplets on hydrophilic beads averaged evaporation times of 40 minutes and decreasing contact angle occurred during evaporation.

KEY WORDS: Energy-Water-Food Nexus, evaporation, soil, wettability, hydrophobicity

1. INTRODUCTION AND LITERATURE REVIEW

The production of food requires adequate fresh water, and the sustainable production of food is a critical focus of the Food, Energy, and Water nexus. Worldwide, agriculture is responsible for two-thirds of water withdrawals because many productive, food-producing areas lack sufficient rainfall to grow crops without irrigation [1]. Surface-level water sources such as ponds, rivers, and reservoirs can serve as irrigation sources but are susceptible to drought [2]. In much of the Great Plains, the Ogallala Aquifer is the primary water source for food production, and is responsible for providing water for over 20% of corn, wheat, sorghum, and cattle produced in the United States. For example, the annual average rainfall in western Kansas is only 12–14 inches and not sufficient for crop growth. As a result, there are 1.5 million acres of irrigated farmland in southwestern Kansas and the Ogallala provides 90% of the water for irrigation [3, 4]. The combination of

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diminishing Ogallala water levels and insufficient recharge rates for the aquifer contribute to the strong need for sustainable water use at the intersection of the Food and Water nexus [4-7]. Reductions in soil evaporation rates will reduce irrigation demands and overall water consumption for crop production, thereby conserving water in the Ogallala Aquifer.

Naturally or artificially hydrophobized soils have been shown to reduce evaporation rates by 50-65% compared to hydrophilic soils [8-11]. Increased hydrophobicity has the potential to impact the mechanisms governing all three phases of transient evaporation through altered contact angles, capillary liquid transport, and enhanced vapor diffusion. There is not a consensus in the literature regarding the relative importance of these evaporation mechanisms [12-15]. Hydrophobicity affects contact angle, contact area, and the air-water interface for evaporating water droplets. Birdi and Vu [16] studied evaporating water droplets on flat glass and Teflon surfaces. For hydrophilic glass, they determined the contact area remained constant and evaporation rates decreased linearly. In contrast, for hydrophobic Teflon the contact angle was constant over time and the interfacial contact line decreased with evaporation; evaporation from the Teflon surface was nonlinear.

Capillary liquid transport plays a strong role in evaporation dynamics for partially saturated conditions [11, 13-15, 17-20]. Shokri et al. [11] investigated unheated sand columns with 18-mm hydrophilic sand/7-mm layers of hydrophobic sand compared to 25-mm layers of hydrophobic and hydrophilic sand. Over 30 days, hydrophobicity reduced evaporation by up to 65%. The authors attributed this reduction of evaporation to the interruption of capillary flow at the hydrophobic/hydrophilic interface. Jury and Letey [21] united the enhanced vapor diffusion theories of Philip and de Vries [22, 23] and Carey [24, 25] by analyzing previous data and noted enhancement factors ranging from 0.75–3.8 in loam, silt loam, sand, and silty clay. For these soil types, Bachmann et al. [26] measured large variations in contact angles (i.e., 0–129^{o}) and yet wettability is not included in these models.

In order to understand the influence of wettability on evaporation, this work investigates evaporation dynamics from a single pore. The research objectives are to understand the impacts of hydrophobicity and contact line dynamics from a pore composed of 2.38-mm hydrophilic glass or hydrophobic Teflon beads; evaporation is visualized using a high speed camera.

2. EXPERIMENTAL APPARATUS

Droplet evaporation in a single, three-bead pore was timed and recorded with HD (High Definition) microscopic cameras (FASTECTM IL3) for top and side views. The bead diameter of 2.38 mm (3/32 in.) and the center to center spaces between each two beads was 2.78 mm. The beads were chosen so that surface tension forces are larger than gravitational forces. The 2.38 mm beads also correspond to a coarse sand in the Unified Soil Classification System [27]. Beads were positioned using an additively-manufacture pocket fixture; with spacing set, the beads were then affixed to the edge of rubber strips using adhesives. Hydrophilic and hydrophobic pores were generated using glass and PTFE beads, respectively. In each test, two 2-μL ± 0.2-μL droplets (i.e., total volume of 4 μL) dyed with red food coloring were placed on the pore using a pipette (Fisherbrand). Videos were recorded at 24 FPS (frames per second) and HD pictures were recorded every three minutes. The camera has a pixel size of 14 μm and is equipped with lens of 0.8 to 9.6 times magnifications. LED lamps provided cool lighting and the temperature and relative humidity monitored were consistently 22.5± 0.5 ºC and approximately 60% RH.

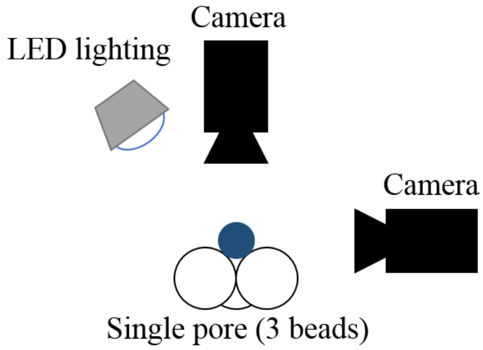


Fig. 1 Schematic of experimental apparatus

Wettability of glass and PTFE beads were measured using goniometer by placing one droplet (4 μL) on glass and PTFE beads respectively, as shown in Figure 2. Due to the lower surface energy of PTFE, droplet was flatter on the glass beads and more curved on PTFE beads. The diameter of contact areas were 1.5 mm on glass beads and 1.1 mm on PTFE beads. Larger diameter and thus larger contact area is reflective of more adherence between the droplet and the bead. During evaporation, it was observed that the contact lines were less mobile on glass beads and more mobile on PTFE beads.

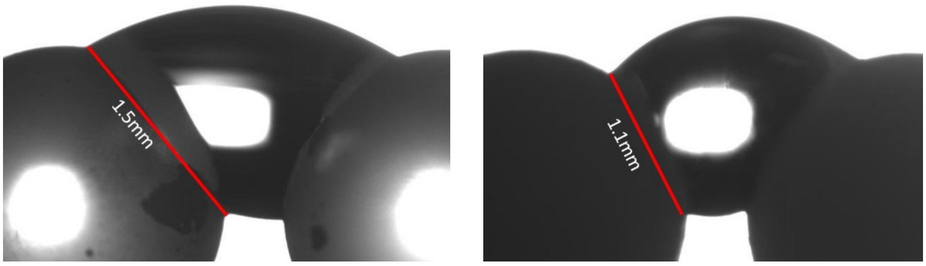


Fig. 2 Wettability of glass (left) and PTFE (right) beads

3. RESULTS AND DISCUSSION

Evaporation experiments were conducted at ambient conditions in both hydrophilic and hydrophobic pores.

3.1 Evaporation time

After the droplet was placed on the pore, pictures and videos were recorded to observe the changes in droplet size during evaporation. The overall time it took the droplet to evaporate was then recorded and can be seen in Figure 3. The average evaporation time on the glass beads for three tests was 40 minutes. The Teflon bead evaporation time was 55 minutes on average for four tests; for all experiments conducted, the evaporation time was longer for the Teflon beads than the glass beads. In addition, the variation amongst the evaporation times for the Teflon beads was much smaller than that of the glass beads.

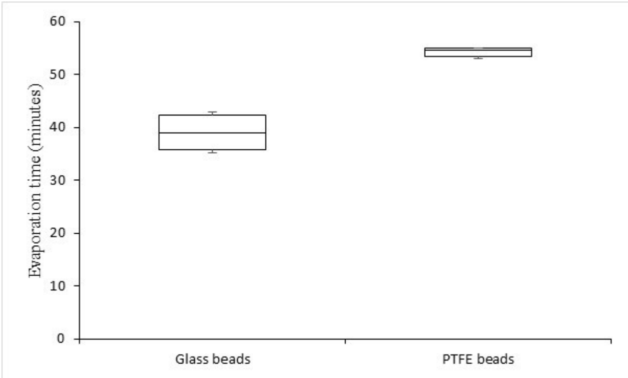


Fig. 3 Box-and-Whisker chart of evaporation times on glass and PTFE beads

3.2 Evaporation– top view

Evaporation times were noted based on observing droplets from the top view. Pictures were recorded from the top view at the start of the experiment, 21 minutes, 27 minutes, 30 minutes, 35 minutes (glass only), 36 minutes, and 42 minutes, as shown in Figure 4 for the glass beads and Figure 5 for the Teflon beads. Comparing to the initial photo, the water droplet on the glass beads has a larger contact area with the beads compared to contact area between the water and Teflon bead. It can also be seen that the droplet on the glass beads has a larger surface area in contact with the air, which contributed to faster evaporation times. This is due to the hydrophilic nature of the glass beads. As seen in the 27 minute photos, the water droplet on the glass beads has broken up, thereby forming two liquid bridges which subsequently narrow due to evaporation. Meanwhile, the droplet on the Teflon bead is still a complete drop spanning all three beads. After 30 minutes, the droplet on the Teflon beads has broken into two liquid bridges spanning two beads. After 35 minutes, the liquid bridges on the glass beads are nearly gone and at 36 minutes the bridges have broken and the drop has mostly evaporated. At 42 minutes one of the liquid bridges on the Teflon beads has broken and one remains.

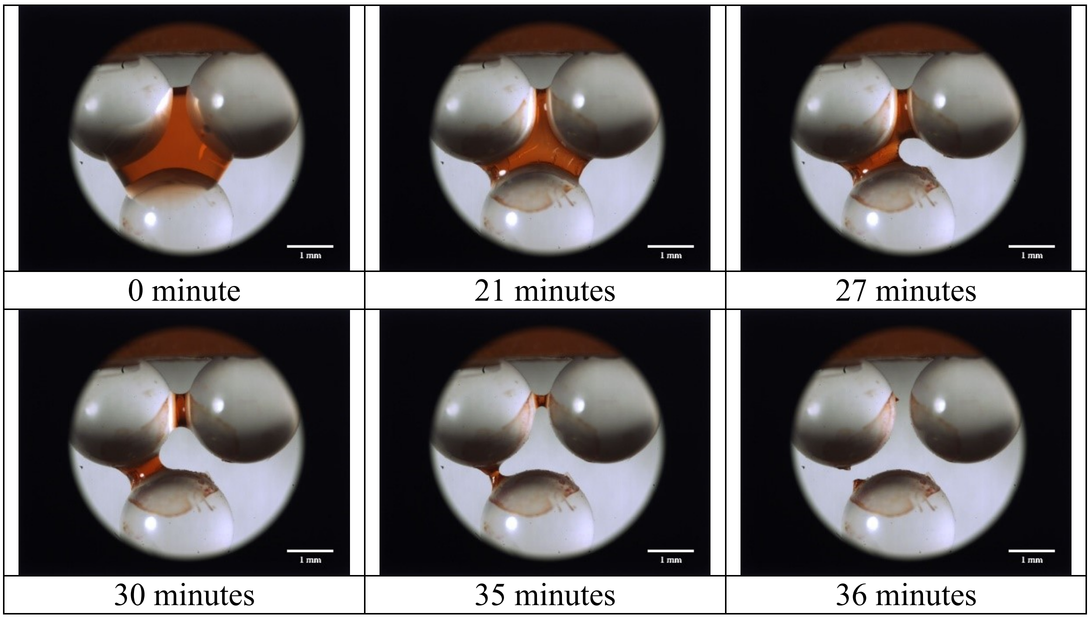


Fig. 4 Top view of a 4-μL droplet evaporating from a hydrophilic pore

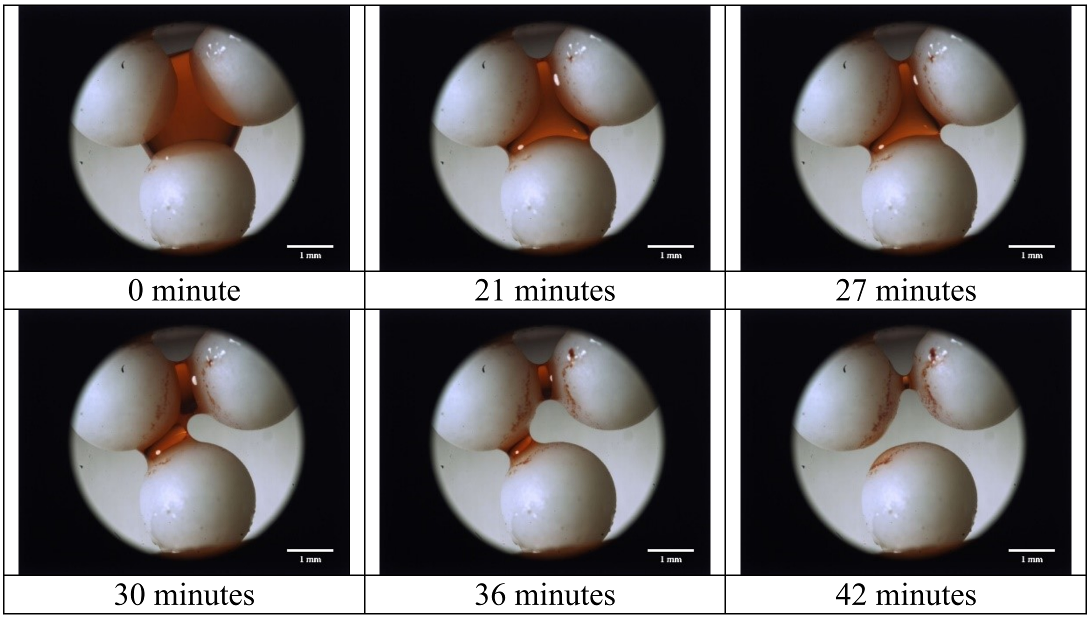
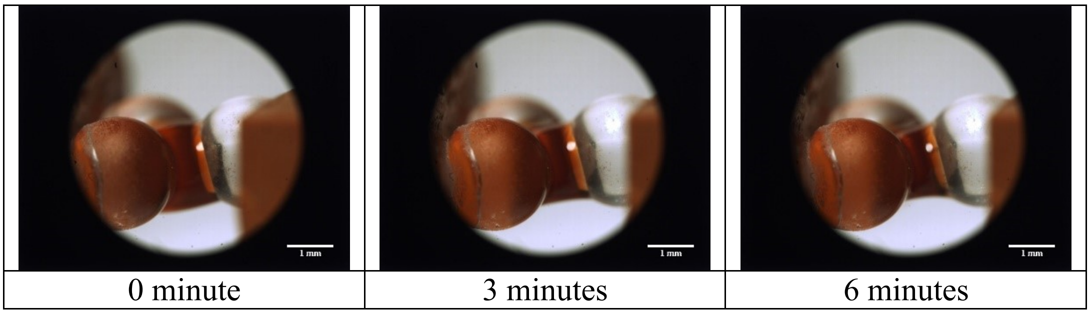


Fig. 5 Top view of a 4-μL droplet evaporating from a hydrophobic pore

3.3 Evaporation– side view

Pictures of the droplets from the side view where taken at the start of the experiments, 3 minutes, 6 minutes, 9 minutes, 12 minutes, 15 minutes, 18 minutes, 21 minutes, and 24 minutes. The pictures can be seen in Figure 6 for the glass beads and Figure 7 for the Teflon beads. At the start of the experiments, the water droplet on the glass bead covers more of the sides of the beads than the droplet on the Teflon beads. However, the droplet on the Teflon bead wets the beads less, and therefore is thicker in the vertical direction. Over the course of the experiment, the droplet on the glass bead has the about the same contact area with the beads while the contact angle changes as evaporation time goes on, particularly evident from 0–21 minutes. The photos show at the start the droplet is beaded up slightly, after 6 minutes the drop is almost flat and occupies about the same contact area with the bead. After 21 minutes, the droplet has a very quadratic line while having roughly the same contact area with the glass bead. In contrast, the water droplet on the Teflon bead has roughly the same contact angle with the beads while its contact area on the beads decreases. The photo at the start has an almost rectangular shape, after 6 minutes the drop has lost contact area with the Teflon beads with a slight decrease in contact angle. Changes in contact area are more pronounced on the bead shown on the left side. After 21 minutes, the contact angle is roughly the same as it was at 6 minutes while contact area with the bead has decreased significantly. These results agree with the results from Birdi and Vu [16] who found that during evaporation on hydrophobic surfaces, the contact angle remains the same and the interfacial contact line decreases while for hydrophilic surfaces, the contact angle decreases while the radius of the contact area remains the same. For both the glass bead and Teflon bead experiments, the droplet breaks at 24 minutes and forms liquid bridges out of view of the camera.



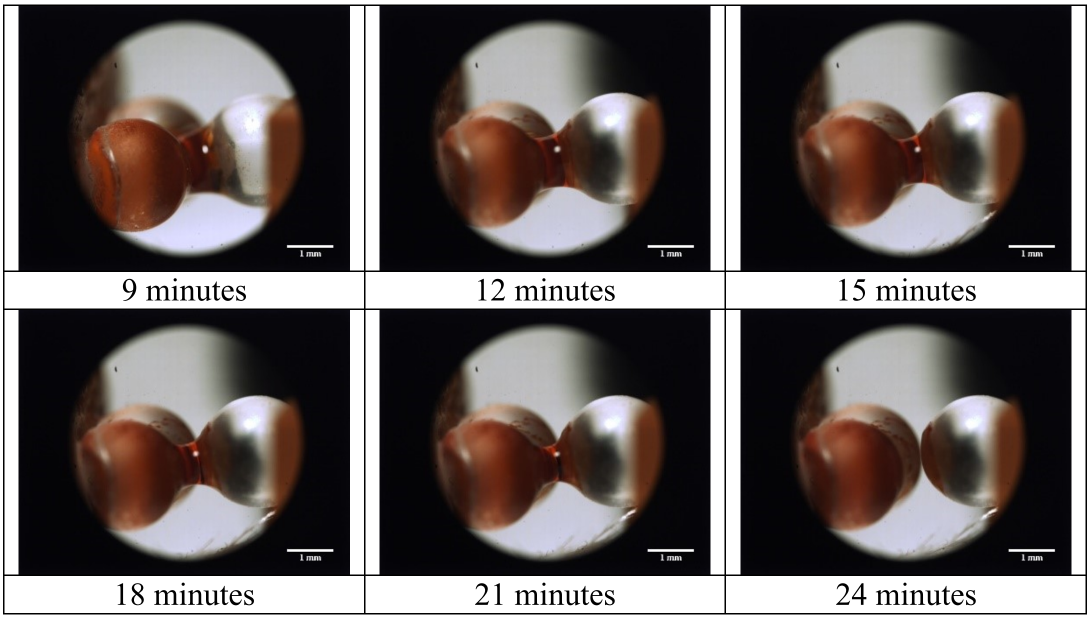


Fig. 6 Side view of a 4-μL droplet evaporating from a hydrophilic pore

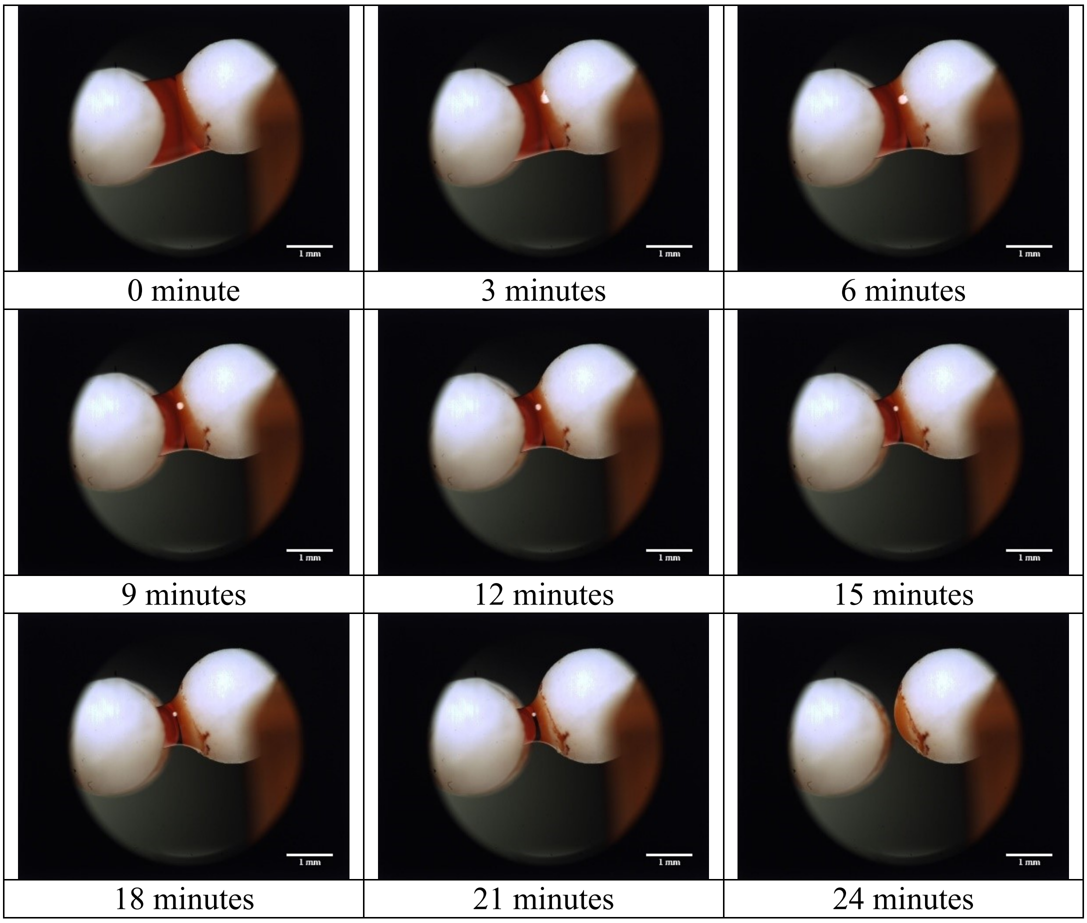


Fig. 7 Side view of a 4-μL droplet evaporating from a hydrophobic pore

4. CONCLUSIONS

Wettability impacts the evaporation process in a single pore comprised of three 2.38-mm diameter glass or Teflon beads through changing evaporation time and evaporation dynamics (e.g., contact line dynamics). After observing the evaporation of a water droplet on glass and Teflon beads, the following conclusions can been drawn:

- Hydrophobicity increases the time needed for a droplet to evaporate (i.e., from approximately 40 minutes on average on the glass beads to 55 minutes on average for the hydrophobic beads).
- Evaporation on hydrophilic beads occurs through changing droplet contact angles.
- Evaporation on hydrophobic beads changes the contact area of the drop.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of NSF CAREER grant number 1651451.

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