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Sustained high evaporation rates from porous media consisting of packed circular rods

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ABSTRACT

Studies of drying from a conventional porous medium, consisting of spheres, have shown the existence of three periods. In the first period evaporation rate is high and essentially depends on the atmospheric demand. Relatively simpler geometry, such as polygonal capillaries, pins liquid along the corner and retains high evaporation rate till a certain extent. We report an experimental study of evaporation from a new, but yet, simpler rod-based porous medium (RBPM) consisting of closely packed vertical circular rods. This configuration can be thought of an '*extreme case*' of a polygonal capillary where the internal angle is zero (0^0). Infrared heating at about $1000\,W/m^2$ causes evaporation from an initially saturated RBPM kept in an acrylic box. We find sustained high evaporation rates until almost all the water is depleted, a feature very different from either a conventional porous medium or a polygonal capillary. *Near-zero radii contacts* between the rods are able to source the liquid, against gravity, to the open end throughout the rod length (75 mm) and thus capillary depinning in all the experiments were forced due to limited liquid content. Using a novel fluorescein dye visualization technique and a simple mathematical model, we show that the corner films present in the near-zero radii contacts between rods results in the high sustained evaporation rate.

1. Introduction

Evaporation from porous media occurs in many natural and engineering systems like soils and heat pipes, and thus has been studied extensively in field and in laboratory experiments. Most of the laboratory studies have been from porous media made up of spheres, both mono-disperse [1] and poly-disperse [2]. We term this type of porous medium consisting of 3D network of pores as conventional porous medium (CPM). In the present work we consider a 'simpler' type of porous medium: vertical, closely packed circular rods, which we term as RBPM (rods based porous medium), which we show has several interesting features compared to CPM. The unit pore in RBPM is the straight region formed by three circular arcs formed by three rods in contact with each other. As we will discuss below, the near zero-radius of curvature at the contact points leads to large capillary forces and the sustained high evaporation rates.

Studies on CPM have shown that evaporation from an initially saturated medium that is confined has three distinct stages. In the first stage, high rates of evaporation are observed; this stage is a constant rate period (CRP) as the evaporation rate is nearly constant [2]. CRP is believed to be due to the presence of liquid near the top surface connected to the bulk through films [3,4]. Various techniques are available to measure the moisture content near the top surface and within the porous samples. The most successful ones are nuclear-based moisture mapping [5–8]. A comprehensive review, comparing different methods of moisture measurement, is presented in Ref. [9]. At some time there is a drastic fall in the evaporation rate and is termed transition regime; various theories have been proposed, including film break-up, for the transition [4]. The time of onset of transition strongly depends on the average pore size [2,10]. In the last stage, the liquid-vapour (L-V) meniscus recedes from the top surface with time and is termed receding front period (RFP) or also falling rate period (FRP).

Stage 1, in a CPM, is sustained by the formation of liquid film(s) which must be connected over a large number of spheres through tortuous paths between the bulk water and the exposed boundary [4]. Any such film will encounter a range of pore scales, and its breakage will depend intricately on this complex pore geometry, a phenomenon not fully understood. At the other extreme of complexity is evaporation from a single vertical pore like that from a polygonal capillary, where the film geometry is much simpler than that in a CPM. Preferential pinning of liquid in the corners of a polygonal capillary has been studied by many researchers mainly during imbibition [11–15].

Combinations of such geometries (square capillaries) were used as a model to explain CRP [16] in a porous medium during its drying. It is clear that films along these corners lead to higher mass transport (than purely diffusion-driven process), compared to a circular capillary, as has been reported [17] from horizontal nanochannels which had a fixed angle (7^0) at one end. The enhanced cooling load capacity of such a porous medium is now used in electronic cooling devices such as heat pipes [18].

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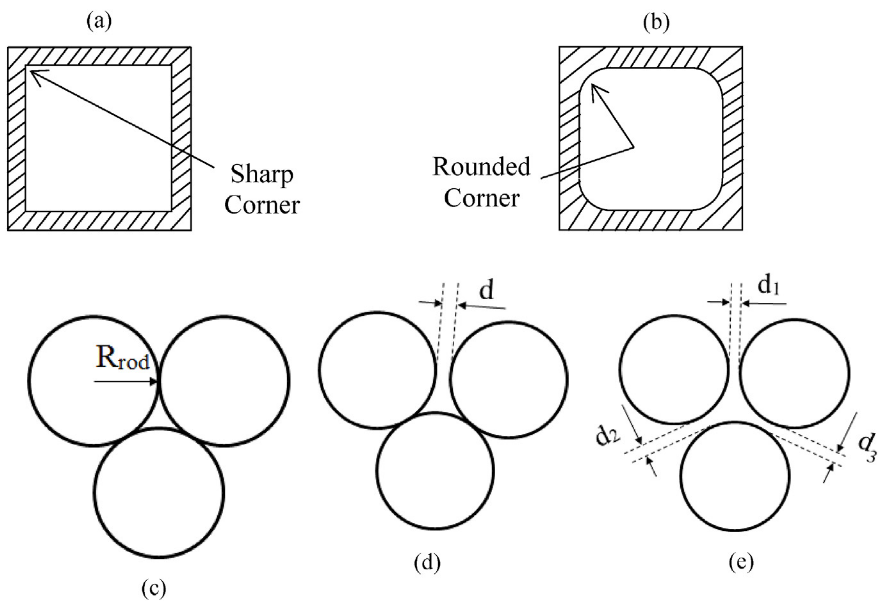

Fig. 1. Schematics showing a four sided capillary with a sharp corner (a) and a rounded corner (b). The geometry (b) is in general produced during the fabrication. The rounded corners reduce the capillary height along it compared to a theoretically zero-radii sharp corner (a). In the present study, three basic types of rods packing patterns, away from the boundaries, are seen in (c), (d), and (e).

Detailed evaporation studies have been reported in a vertical square capillary [19,20] and in a horizontal rectangular capillary [21], the former having four corner films and the latter two. In both of these experiments, done in an isothermal environment, a CRP followed by a FRP was reported. Further during CRP reduction in the evaporation rate observed by Ref. [19] was argued to be due to the continuous thinning of corner films. For the horizontal capillary case, the corner film thickness was nearly constant in CRP [21] and a constant evaporation rate was observed. In the vertical capillary [19,20] FRP followed after the film depinned against gravity and for the horizontal capillary [21] depinning was not observed and change in the meniscus geometry was argued to be the reason behind FRP. In the former experiment, heptane was used, the film depinning length increased nearly thrice [20] when the radius of curvature of the square capillary corner was reduced from 100 μm to 20 μm.

The present study is concerned with evaporation from pores formed between three contiguous circular rods in vertically stacked RBPM. Fig. 1 shows pore geometries obtained in capillaries with sharp (a) and rounded (b) corners, with three rods in perfect contact (c) and with gaps (d, e). Capillary height rise in a capillary increases as the corner radius decreases with sharp corners giving an infinite rise height. Similarly smooth circular rods in perfect contact will result in infinite capillary rise, and any gaps will give a finite rise height. In practice, polygonal capillaries with sharp corners cannot be manufactured and will always have rounded corners. For the case of three rods in contact, the rise height will be limited by combination of waviness or roughness of the rods surfaces and inevitable gaps due to imperfect contact. Using solutions given by Refs. [22,23] for geometry of the meniscus of liquid rise between two and three rods, we obtain the film height for d/R_{rod} of 0.001, 0.01, and 0.1, with water (pentane), to be 7.5 m (3.1 m), 720 mm (303 mm), and 24.8 mm (11.7 mm) respectively when 3 mm diameter rods are considered. For a 0.7 mm diameter rod, the corner meniscus rise for water is about 30 m for $d/R_{rod} = 0.001$. In the present experiments, 3 mm and 2 mm glass rods and 0.7 mm pencil rods were used and the rod heights were 75 mm. As will be described below, except for some defects where gaps existed, most of the rods were tightly packed. Thus in most of the pores, the capillary film rise height would be expected to be much more than the rods height.

The aim is to experimentally investigate the evaporation characteristics from this new type of porous medium under controlled IR heating. The stacked rods in RBPM allows applications to devices and for fundamental studies of corner film evaporation under high heat limits, including one where viscous forces become significant.

2. Experimental methodology

All the experiments were conducted with an acrylic box having a height of 78 mm and 51 mm × 41 mm as the cross-sectional dimensions. Circular cross-section rods (2 mm & 3 mm diameter glass and 0.7 mm diameter pencil rods) were vertically stacked in the acrylic box; the height of the rods was 75 mm. Two liquids, water and n-pentane were used in the experiments; both the liquids wet the glass and pencil rod surfaces. At a temperature of 25 °C, the density, surface tension, and dynamic viscosity of water (and n-pentane) are respectively 997 (626) kg/m^3, 71.99 (15.79) mN/m, and 0.89 (0.24) mPa-s. Whereas the glass rods (Spectrum marketing, Mumbai, India) have smooth surfaces, the pencil rods have about ~10 μm longitudinal grooves seen under a microscope and confirmed using a micro CT scan. The impact of rough rods is discussed elsewhere. The HB pencil rods are stated by Faber-Castell to be made of super polymer lead. In the experiments, the RBPM was initially saturated. In all the experiments, however, a 2–3 mm layer of liquid was added on top, which enabled us to obtain, as reference, the evaporation rate from a bare liquid surface. Fig. 2(a) shows the experimental setup. Evaporation from the porous medium was boosted by the use of an infrared (IR) heater. The IR heater was 20 cm × 20 cm in size and was placed directly above the RBPM at a distance of ~18.5 cm. Uniform heat flux is therefore obtained throughout the 51 mm × 41 mm sample surface. Note that the IR radiation used in the current experiments almost all the radiative energy was between wavelengths $3\mu m$ and $5\mu m$. In case of glass, these radiations are absorbed within a distance of ~0.1 mm; for pencil rods this distance is even smaller. Thus effectively all the radiation is absorbed at the surface and none are transmitted. Evaporation rate was obtained by measuring mass loss with time using a precision weighing balance (Sartorius GPA5202) having a least count of 0.01 g. The top surface temperature of the porous medium was measured using a thermal camera (Fluke Ti400) while a T-type thermocouple was used to measure the temperature of the bottom (outer) surface of the acrylic box. Since the IR heater was placed directly above the sample, the thermal camera was put at an inclination of ~25^0 to the vertical; this did not affect the surface temperature measurement. The thermal images were taken by temporarily blocking the incoming IR radiation (for about 5 s) to remove reflected radiation from the RBPM surface; not doing this introduced error in the temperature measurement of 5–6 °C for an IR