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

Navneet Kumar*, Jaywant H. Arakeri

Department of Mechanical Engineering, Indian Institute of Science, India

A B S T R A C T

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°). Infrared heating at about 1000 W/m² 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 was 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°) 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].

* Corresponding author.
E-mail addresses: navneet01011987@gmail.com, navneetkumar@iisc.ac.in (N. Kumar).

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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 300 mm to 20 mm.

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 $d/R_{rod} = 0.001, 0.01$, and 0.1, with water (pentane), to be 7.5 mm (3.1 mm), 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 mm 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 3μm and 5μm. 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° 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
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radiation intensity of 1000 W/m². This temporary blockage also avoids any effect due to the shiny rods’ surfaces. To minimize heat loss to the ambient, the acrylic box was insulated with 50 mm thick Styrofoam on the four vertical sides and the bottom. Reflective aluminium foil was put on the top face of the insulation, and on the sides to reduce unwanted heating of the RBPM. A small amount of fluorescein dye was added to the water to track the evaporation sites. The dye when in solution is green and is orange when dry. This property allowed us to distinguish regions which are still wet (green) and regions where the water from the surface has fully evaporated leaving behind orange dye particle deposits.

Preparing the RBPM is important and we followed a packing protocol for the same; we discuss it briefly next. The container (acrylic box) was filled completely with the desired liquid initially and was tilted as the rods were packed. The rods were placed layer by layer which results in water spilling out of the box corresponding to the volume of the rod (s). We noticed that, unlike a CPM where spheres settle upon shaking, shaking was not required in preparing a RBPM. The last few layers cannot be packed using the mentioned procedure and thus the rods were pushed, at multiple locations, with force to get maximum packing fraction. Once fully packed, the excess liquid was removed carefully in order to get the saturated (100%) amount of liquid in the RBPM; at this saturation the liquid level matches with the top surface of rods. Finally 2–3 mm of liquid was put on top of the RBPM intentionally so as to get the potential evaporation rate. During the packing, n-pentane had to be put on the top face of the insulation, and on the sides to reduce un-effective aluminium foil was put next. The container (acrylic box) to have the rods sticking to the walls at all places, and two, due to presence of defects in the interior; for the 3 mm rods (with water) case the difference is about 1.89%. Fig. 1(d) and (e) illustrate the gaps that can occur due to defects; similarly, all rods would not be in perfect contact with the side walls and such gaps would be present at the walls as well. For comparison, the theoretical porosity value for mono-disperse closely packed spheres is 25.95%, whereas in experiments values between 31 and 38% [10] have been obtained. In soils, the porosity is between 40% and 45%. Note that for RBPM, the areal porosity at any horizontal cross-section including at the surface will be approximately same as volume porosity.

Two characteristic pore sizes may be defined for RBPM, one corresponding to the bulk meniscus and the other corresponding to the corner film. The larger pore size may be calculated based on the cross-sectional open area or void between the three rods; we get pore diameter = 0.62 Rrod. This value is almost same as pore diameter calculated for CPM consisting of spheres, where pore size = 1/3 (sphere diameter). The second pore size is ‘d’, gap between adjacent rod surfaces (Fig. 1(d) and (e)), which determines the rise height in the ‘corner’ film. These definitions assume that d/Rrod is small. The larger pore size determines the bulk meniscus height, and the smaller pore size determines the film rise height. In the limit of d → 0, the film rise height, as discussed above, is infinity. As we shall see below, the liquid from the bulk meniscus feeds into the film region. In the context of CPM, a similar connectivity was discussed between two hydraulically connected capillaries of different internal diameters [2], the larger capillary supplying liquid to the smaller one.

### Table 1

<table>
<thead>
<tr>
<th>Rod Dia. (mm)</th>
<th>Exp. ϕ (%)</th>
<th>Theor. ϕ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass (GR); 2.0</td>
<td>18.88</td>
<td>15.26</td>
</tr>
<tr>
<td>Glass (GR); 3.0</td>
<td>18.05</td>
<td>16.16</td>
</tr>
<tr>
<td>Pencil (PR); 0.7</td>
<td>12.63</td>
<td>11.82</td>
</tr>
<tr>
<td>n-Pentane; 2.0</td>
<td>18.84</td>
<td>15.26</td>
</tr>
<tr>
<td>n-Pentane; 3.0 (No heating)</td>
<td>17.36</td>
<td>16.16</td>
</tr>
</tbody>
</table>

3. Results & discussion

We now present results with external top heating for an experiment with water. Fig. 3 shows variations of temperature and evaporation rate with time for a RBPM consisting vertically stacked 2 mm diameter glass rods. The excess water evaporates at around 3 h leaving the top surfaces...
of the glass rods exposed to the IR radiation. The evaporation rate reduces gradually after this time, till about 22 h when there is a sudden drop. The high evaporation rate period is similar to CRP observed in CPM and in capillaries with corner films, but as we shall see below, the sudden drop is not due to the film depinning leading to FRP. The average top surface temperature, captured using the thermal camera, shows a gradual increase during the first stage, necessitated by the reducing latent heat loss to be made up in increased convective and radiative heat losses to the ambient. IR images were not captured during $t = 8$ h and $t = 16$ h; the surface temperature trend is clear though. After the end of first stage, there is a large increase in surface temperature. Temperature at the bottom of the acrylic box also shows a gradual increase in the first stage while the transition to a higher value in the second stage is delayed due to the thermal inertia of the system. During the experiment, the ambient temperature was nearly 25 °C and the relative humidity (RH) varied between 48% and 56%. Increase in the surface temperature, in stage 2, was also reported in Ref. [24] where experiments (without external heating) were conducted, in the presence of wind, with spheres having a size range ($0.70 \pm 1.20$ mm).

The change in surface temperature during the transition from CRP to FRP was 4.5 °C for wind velocity of 0.8 m/s, and it was 2 °C for a velocity of 0.3 m/s.

A different view is obtained by plotting evaporation rate versus saturation (S), where S is the ratio of liquid mass at any time to that when pores are completely filled. Fig. 4(a) shows these variations for three types of RBPM (0.7 mm pencil rods and 2 mm & 3 mm glass rods) and one CPM consisting of 0.70–0.85 mm glass spheres; all experiments being done with water. For the CPM case, we observe the conventional stages of evaporation, with FRP at S ~ 0.7, corresponding to an average water level of about 30 mm below the top surface. In contrast for similar sized pencil rods case, most of the water (~85%) gets evaporated in the first stage. The transition at 15% saturation corresponds to a water level 70 mm below the top surface, just about 5 mm above the acrylic box base. However, as is discussed below much of the remaining water is not at the bottom, but in the films and defects.

For the 3 mm and 2 mm glass rods cases, the transitions are at slightly different values, at about $S = 0.2$ and 0.1 respectively. These small differences in the transition points with rod diameter for RBPM is very different from what is observed in CPM where transition saturation point depends strongly on sphere diameter; for example, transition for CPM with 3 mm glass spheres is when water level is about 10 mm [10] below the top. Unlike in the case of CPM, the transition to second stage in RBPM is because nearly all the water has been consumed in the first stage and there is very little water left for evaporation. RBPM consisting of 2 mm diameter glass rods saturated with n-pentane had very high evaporation rates, nearly 20 times, compared to the water cases; the point of transition, however, is similar to that for water.

Non-dimensional numbers governing the evaporation process are Capillary (Ca) and Bond (Bo) numbers, defined as:

$$Ca = \frac{\mu V_l}{\sigma} \quad Bo = \frac{\Delta \rho \rho g R^2}{\sigma}$$

where $\mu$ and $\sigma$ are respectively the dynamic viscosity and surface tension of the evaporating liquid, $V_l$ is the liquid velocity scale in the corner films, $\Delta \rho$ is the difference in densities of the evaporating liquid and the displacing (air and liquid vapour mixture) phase, $g$ is the gravitational acceleration, and $R_m$ is the radius of curvature of the bulk meniscus in the unit cell of the packed rod arrangement. These definitions are same as in Ref. [20]. Corresponding to the least (~20 mm/d in case of water with heating load of ~1000 W/m²) and the highest (~400 mm/d in case of n-pentane with heating load of ~1000 W/m²) evaporation rates, the liquid velocities ($V_l$) in the corners are nearly 0.02 mm/s and 0.31 mm/s respectively. The ranges of Ca and Bo in the present experiments are therefore 1E-07 to 5E-06 and 9E-03 to 3E-02 respectively. Note that these values are of similar orders to the ones used in the numerical modeling [20]. The low value of Ca implies that viscous forces are negligible.

We performed experiments without IR heating to compare the results with the heating case. For the former experiment the container sides were not insulated. In both of these experiments n-pentane was used as the evaporating liquid. Fig. 4(b) shows the evaporation rates plotted versus S. In both the experiments CRP lasted till saturation of 0.1 i.e. 90% of n-pentane was evaporated in the first stage. The evaporation rates in CRP were 200–300 mm/d and 350–400 mm/d for the non-heating and heating cases respectively. The respective latent heat losses are therefore 500–800 W/m² and 900–1000 W/m² respectively. Note that the required latent heat in non-heating case comes from the ambient (25 °C) either directly to the rods top surfaces or through the container walls; the surface temperature in the first stage is lower than the ambient. Similar heat transfer mechanism would have led to evaporation in the isothermal experiments with single capillaries [19–21]. We observe that with RBPM the externally supplied heat increases the evaporation rate but the regimes and transition to FRP remained essentially same. Also note that the glass rod diameter, 2 mm and 3 mm for heating and non-heating cases respectively, has hardly affected the transitional saturation value.

The results show that the film depinning length, connected with end of CRP, is considerably higher compared to that obtained in a vertical square capillary tube with rounded corners, where it was found that the depinning length depends on both radius of the corner and the liquid. With heptane, the depinning length was 12 mm for corner radius of 100μm [19] and 32 mm for corner radius of 20μm [20]. For the larger radius tube, the depinning length reduced to 6.5 mm for 2-propanol. It was argued that reducing the radius to zero would increase the depinning length. In the present geometry near-zero radii of contact (due to perfect corner) is achieved, and the depinning length, for similar Ca and Bo, was found to be essentially independent of the type of liquid, the rod diameter, and the external heat load.

Film depinning length has been theoretically estimated for a square capillary with sharp corners (Fig. 1(a)) [25] for a combination of Ca and Bo where drying was allowed to occur in the presence of a convective boundary layer and gravity. Even though the geometry is different, the theoretical predictions for a square capillary give an idea of the depinning lengths to be expected for RBPM. We estimated the film depinning length, following [25], to be about 370 mm for a 3 mm diameter rod when Bo = 0.01 and Ca = 0.001. As stated above, in our experiments, the range of Bo is 9E-03 to 3E-02 and range of Ca is between 1E-07 and 5E-06; the Ca values are much lower compared to the
ones considered in Ref. [25]. In our experiment, with a 3 mm diameter rod and n-heptane, \( \text{Ca} = 0.001 \) would require a evaporation rate of \( \sim 60 \text{ mm/s} \) which is 200 times more than the present experimental value of \( \sim 0.3 \text{ mm/s} \), which would give theoretically much larger depinning length than 370 mm. Such high evaporation rates are irrelevant for our experimental conditions. For a lower \( \text{Bo} \) corresponding to a 2 mm rod and \( \text{Ca} = 0.001 \) the film depinning length is much higher, \( \sim 100 \text{ cm} \). Thus theoretically expected film depinning lengths are much larger than the rod lengths in the present investigation. Only at very high evaporation rates \( (\sim 100 \text{ mm/s}) \), which may be obtained in heat pipes and other cooling devices, will viscous forces will become of the order of capillary forces which might reduce the depinning length as suggested in Ref. [25]. In the present experiments, depinning length is a result of balance between capillary and gravitational forces with negligible viscous effects. For a horizontal capillary, because of absence of gravitational forces the depinning length would become limitless, at least as long as viscous forces are small compared to the capillary forces as reported in Ref. [21], where it was found that only after the bulk meniscus reached the end of the tube, the corner films started thinning and evaporation rate started falling.

Since the end of CRP is unlikely to be due to depinning (at least in the tightly packed regions), we need to account for volume of water remaining at the end of CRP. It is expected that the depinning length would be very large for RBPM, certainly more than 75 mm, height of the porous medium. We conducted a few isothermal experiments with three glass rods (3 mm diameter) in mutual contact, in both vertical and horizontal orientations, and introducing water or n-pentane in the pore. In the vertical orientation, the bottom was closed and the bulk meniscus travelled towards each other and merged quickly. These experiments with a unit cell showed that there was no depinning. However, as discussed above, experiments with large number of rods (Fig. 4) show that S lies between 0.05 and 0.2 at the end of CRP. We show that these values of S at end of CRP are partly due to improper packing (which is inevitable with large number of rods in a square box). To provide an estimate of remaining mass of water in the experiments with large number of rods, consider the worst case of RBPM consisting of 3 mm diameter glass rods with water where \( S = 0.2 \) at the end of CRP. For three rods in perfect contact (Fig. 1(c)), using corner film geometry [22] and properties of water, we estimated that nearly 5–6% of the initial water is trapped in the isolated films when the bulk meniscus is at the bottom. There can be some liquid remaining at the bottom because bottom surface of the rods is not perfectly flat; we estimate this amount to be 1%. The remaining \((\sim 10\%)\) water is present in the imperfectly packed regions (Fig. 1(d) and (e)). Similar gaps would also exist between rods and the container walls which would also hold some liquid at the end of CRP. For the simplified case \( (d_1 = d_2 = d_3 = d, \text{Fig. 1(d)}) \) assuming \( d/R_{\text{rod}} = 0.1 \), the height (against gravity) of corner and bulk menisci [22,23] are nearly 25 mm and 17 mm respectively; water trapped is nearly 0.14 cm\(^3\) in such a unit cell. The number of rods used in this particular experiment was nearly 250 and if we assume that 25 (10% of total number) unit cells were not perfectly packed at the end of CRP these unit cells will hold nearly 3.5 g of water compared to the total saturated mass of water of 28 g accounting for \( \sim 13\% \) of water at the end of CRP. The numbers of these imperfections are assumed based on the measured porosity value; exact numbers of imperfections can be obtained by counting them (a difficult and exhaustive procedure) throughout the top surface. For a RBPM where there are no imperfections, saturation value lower than 0.1 is therefore expected at the end of stage 1. We may note here, in the experiments with RBPM, wherever there was proper contact between rods and the wall, we could observe from the fluorescein dye images at end of CRP that the bulk meniscus locally had reached the bottom, in agreement with experiment done with three rods in contact.

To understand the evaporation during CRP stage, we need to look at the water film rising to the top along the contact lines between adjacent rods (Fig. 5(a) and (b)) or between rods and a wall (Fig. 5(c) and (d)). The contact line has theoretically a zero radius of curvature and the liquid can rise to infinity due to capillarity [22,23]. The green colour in Fig. 5(c) is due to the fluorescein dye that was added in the water. Thus, in RBPM, these films rise to the top at all times during the experiment to enable high sustained evaporation rates until the water is almost depleted. As discussed above there will be no film depinning till the bulk reaches the bottom at those regions where there is perfect contact between adjacent rods, and between rods and the container walls. After the start of the experiment, with time, the bulk meniscus goes down but the films are present till the top. Each pore and the associated films are independent of each other unlike in CPM, where films are interconnected laterally and vertically.

Addition of small amount of fluorescein dye in the water allows us to visualize the evaporation sites [10]. The added fluorescein was 0.6% by volume and this small content is not expected to significantly change the evaporation behaviour and the depinning length [26]. The technique is similar to that used in CPM in Refs. [26] and [27], except that in the former colloid particles were used as tracers. When in solution,
the fluorescein appears green and fluorescein particles, orange in colour, deposit on the solid surface at the sites where the final film of water evaporates (see Fig. 5c)-(e)). Almost all the deposits are concentrated in the top 15 mm of the glass rod, which indicates that film evaporation occurs in this region throughout the experiment. Thus, liquid is transported via the corner flow to the top where the final evaporation occurs. Simulations of evaporation under isothermal conditions in vertical and horizontal capillaries [20,21] showed significant evaporation was limited to short distances from the open ends of the tubes while rest of the film was exposed to nearly fully saturated vapour mixture. The heating and higher temperature along the corner film in the present case is expected to alter the evaporation processes, but it seems that evaporation in RBPM is also limited to 10–20% of the film length, as also revealed by the mathematical model below.

4. Mathematical model for rod/bulk meniscus temperature

How the evaporation rate varies with depth is an important question. We can get an idea of this variation using a simple heat transfer model. Assuming quasi-steady conditions, the 1-D heat conduction equation in the rods at any instant is:

\[ KA \frac{dT}{dz} = Q' \]  

(2)

where, \( T \) is the rod temperature, \( Z \) is vertical distance from the top surface, and \( K \) and \( A \) are the thermal conductivity and cross-sectional area of the rod respectively. \( Q' \) is the heat transfer rate per unit length due to evaporation, and will be present from the top surface \((Z = 0)\) to the bulk meniscus \((Z = L_m)\). To solve Eq. (2), we assume \( Q' \propto (L_m - Z)^{4+p} \) after we rejected a few other possibilities [28]. For the temperature boundary conditions, we used the measured temperatures at each instant at the top surface \((T_{top})\) and at the bottom of the acrylic box \((T_{bot})\) which is assumed to be equal to the temperature at the bulk meniscus.

at \( Z = 0, T = T_{top} \); at \( Z = L_m, T = T_{bot} \)  

(3)

The second boundary condition in Eq. (3) implies that the temperature gradient in the saturated region \((Z > L_m)\) is negligible. This assumption is justified as the bottom of the container is insulated and very little heat is lost to the ambient from the vertical sides and the bottom surface of the container. The total evaporative heat loss \((Q_{Lat})\) obtained from the measured evaporation rate is

\[ Q_{Lat} = \int_0^{L_m} Q'dZ \]  

(4)

In the formulation, we neglect sensible heat transfer to the water vapours, and assume heat conduction in the corner liquid film is negligible compared to that in the rods. The total heat energy stored in the RBPM during the first stage was neglected as it was just 3% of the incident radiation heat energy. Solution of Eq. (2) is

\[ T = T_{top} - \left( \frac{1}{KA} \left( \frac{Q_{Lat} L_m}{3+p} \right)^{1+p} \right) \left[ 1 - \left( \frac{L_m-Z}{L_m} \right)^{1+p} \right] \]  

(5)

At any time we calculate the value of \( p \) from the known values of \( L_m \) and temperature at \( Z = L_m \). The values of ‘\( p \)’ were 1.96, 1.53, 1.13, 1.21, 0.96, and 0.81 when \( L_m = 21 \) mm, 31 mm, 41 mm, 51 mm, 61 mm, and 71 mm respectively. In the absence of any theoretical or physical basis for the evaporation process in the films region, we arrived at this model for \( Q \) which satisfies the known boundary conditions. We note that the results are not very sensitive to the exact value of \( p \). The proposed model seems to capture the essential features of evaporation from the RBPM. Note that some other profile for \( Q' \), for example equal to a constant, will not satisfy the temperature boundary at the bulk meniscus [28].

Fig. 6 shows the profiles of non-dimensional \( Q \) corresponding to several positions of the bulk meniscus. Evaporation per unit length decreases non-linearly with depth. We see that, at any instant, most of the latent heat release or evaporation occurs near the top; \( Q \) at the top \((Z = 0)\) is about three times the average value, and decreases with increasing \( L_m \). This result is consistent with the high concentration of fluorescein dye deposits at the top ends of the rods. Inset on the left side in Fig. 6 shows the corresponding temperature profiles, which when non-dimensionalised shows reasonable collapse as seen in inset on the right side. Further investigation is required to establish the relation between the film characteristics, like film width at any height, and the evaporation rate there. The basic question remains: what determines \( Q' \) at any height?

A complete mathematical model will require calculation of the heat conduction in the rods, of liquid and vapour flows and of the
evaporation at the liquid film. For the vapour part, the concentration diffusion equation will be valid since the largest Peclet number (Pe), for n-Pentane case is approximately 0.1. But the vapour concentration will also depend on the vapour temperature which in turn depends on the local film and rod temperature. It is important to note that most of the evaporation is known to occur on a very thin film at the edge of the meniscus over a short length of a few microns [29–31].

Fig. 6. Height-wise variation obtained from the model of latent heat loss per unit film length for different bulk meniscus locations $L_m$ Corresponding height-wise variations of temperatures are shown in the left inset. Right inset shows evaporation at the liquid film.

The model would thus have to include the evaporation thin film theory in addition to calculation of temperature and the gas phase concentration distributions. A corner meniscus, as in the present case, offers elongated regions, as shown in Fig. 5(b), over which evaporation occurs. A simple extension of the models [19–21] used for isothermal evaporation in polygonal capillaries to the present case with heating is not possible. Theirs was essentially a Stefan-tube type formulation, applied to corner films, where the energy equation is not required.

In summary, it is clear that films along zero-angle contacts between adjacent cylinders are responsible for the observed high sustained evaporation rates. In the present experiments, depinning is unlikely to have occurred in regions where there was perfect surface contact and the sudden drop in evaporation rate was due to depletion of the liquid. The liquid remaining at the end of CRP was on the surfaces of the rods, at the bottom of the box, and in the defects and walls due to the imperfections. Even though the theoretical film rise height along the zero radii of curvature contacts between surfaces of adjacent rods is infinity, practically, the waviness and roughness of the surfaces will eventually limit the rise height; experiments with long enough rods are expected to show the true film depinning length and true transition from CRP as in square tubes with rounded corners. In the present RBPM experiments, with 75 mm long rods, duration of CRP was nearly independent of rod diameter and type of liquid [32].

Experiments with the vertically stacked rods, is a study of evaporation of water in a new and simpler type of porous medium under controlled radiative heating and with adiabatic conditions on the sides and bottom. There are some similarities with evaporation of volatile liquids from single square tube [19–21], modelled as a diffusion controlled phenomenon under nearly isothermal conditions. The corner films in the RBPM offer higher areas for evaporation, which are near the top end as indicated by the sites of deposited dye. Results from RBPM will be useful for developing models for evaporation processes in regular porous media, like soils under solar insolation. In addition to being useful for fundamental studies, RBPM would be useful for developing cooling devices with high heat dissipation made possible by corner films which is achieved easily by stacking smooth surface rods. The characteristics of the RBPM at much higher heat fluxes ($\sim 10^5$–$10^7$ W/m$^2$) need to be investigated when viscous forces will not be negligible in comparison to the capillary forces.

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Appendix A. Supplementary data

The data required for regenerating the results reported in this article is available at “https://figshare.com/s/85482440d4f280ec3e4” or “https://doi.org/10.6084/m9.figshare.6881609”. Supplementary data related to this article can be found at https://doi.org/10.1016/j.ijthermalsci.2018.07.035.

References


[28] For the heat transfer model we used different relations for Q such as $Q' = \text{constant}$, $Q' \propto (L_m - Z)$, and $Q' \propto PZ$ where $PZ$ is the film perimeter at any $Z$ plane. All these formulations led to unphysical situation since they under-predicted the bulk meniscus temperature by large margins.


[32] The observed depinning length for a conventional porous medium, consisting of 0.70-0.85 mm diameter glass beads, were nearly 26 mm and 19 mm with water and n-Pentane respectively. With same material dimension in RBPM the observed depinning lengths were nearly same for both the liquids. In order to get true depinning lengths experiments with much longer rod lengths need to be conducted. The limitation in case of longer rods, their flexibility and uniform desired roughness, makes it extremely difficult to validate this point.