ULTRA-RAPID AND RELATIVE HUMIDITY-INDEPENDENT DRYING OF NANOCHANNELS

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ABSTRACT

We observed that water-filled nanochannels dried up to 1000 times faster than predicted by vapor diffusional drying. Here we show that this ultra-rapid water transport is caused by very sharp channel corners siphoning (wicking) the water to the channel exit before it evaporates. Evidence is also provided that these sharp corners make the drying process independent of the relative humidity (RH) of the environment up to an RH of more than 0.9. To our knowledge this is the first time that nanochannel drying has been observed, and both the acceleration of drying and the independence of RH are highly surprising.

Keywords: Corner flow, drying, nanofluidics, wicking

1. INTRODUCTION

Drying processes are important in the pharmaceutical, food and agricultural industry as well as in soil science. Capillaries or channels offer the simplest drying model. When capillaries or channels are dried in the atmosphere, water transport can take place by three processes, namely vapor diffusion, by flow in a thin water film adsorbed to the surface or by flow in corners or grooves (see figure 1) [1]. By using an array of sharp-cornered nanochannels of different width, we were able to quantify corner flow.

2. THEORY AND EXPERIMENTAL

We assume that channels dry by three water transport processes to the environment: film flow, corner flow and vapor diffusion (figure 1). Theory predicts that the drying rate decreases with the square root of time and equals

$$\frac{L^2}{t} = C_v + \frac{C_f}{h} + \frac{C_c}{wh}, \qquad (1)$$

where L is the total dry length of channel, C_v, C_f and C_c indicate factors related respectively to vapor flux, film flux and corner flow, h is the channel height and w the channel width. As can be seen from eq.1, only the drying by corner flow depends on the channel width. If we observe a dependence of drying rate on channel width, this will therefore indicate that drying proceeds predominantly by corner flow. The magnitude of the corner flow strongly depends on the sharpness of the corners as demonstrated in figure 2. Corner flow in one 12 degree corner is 165 times larger than corner flow in two 90 degree corners for geometrical reasons and because of the decreased flow resistance [2].

We produced arrays of 75 nm high Pyrex nanochannels of 4 mm length and with widths from 2 to 30 micrometer by wet etching and fusion bonding. Corner angles were

0-9743611-1-9/µTAS2005/$20©2005TRF

12° due to under-etching of the photoresist. Channels were filled with water and drying was observed as a function of RH in a regulated humidity chamber. Channels dried from both sides, and total dry length *L* was recorded.

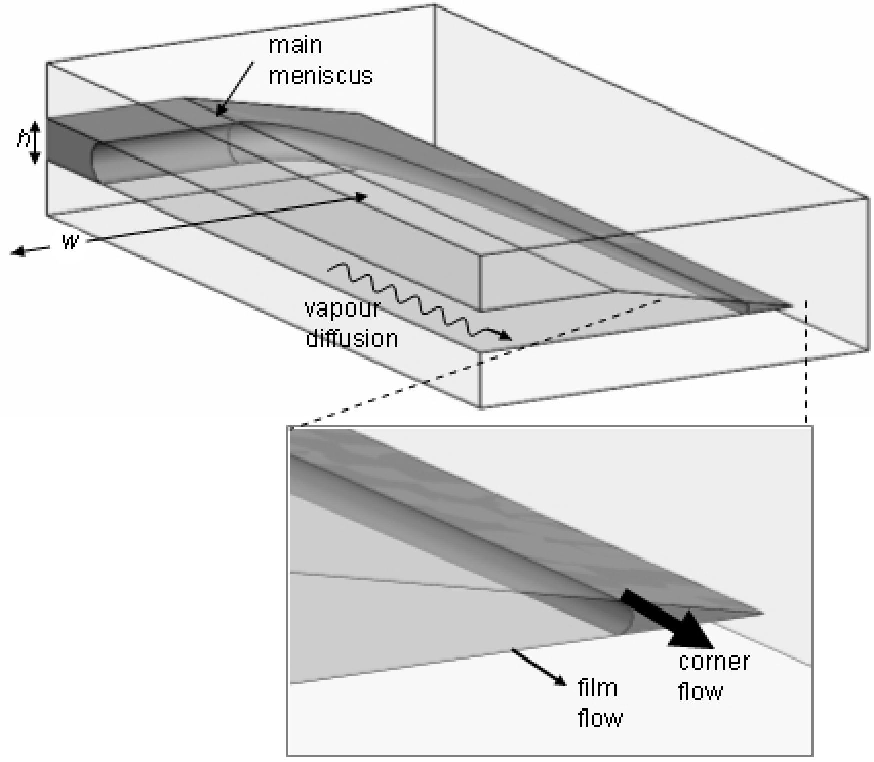

Figure 1 Vapor diffusion, film flow, and corner flow, contribute to the water flux out of the channel and make the main meniscus move backwards. Channel has height h and width w.

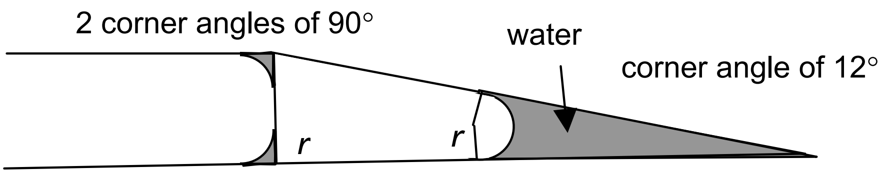

Figure 2 At any meniscus radius r (determined by the local RH) much more liquid is held in acute-angled corners than in blunt ones. Because the flow resistance is also smaller for sharper corners [2], acute-angled corners strongly enhance liquid transport.

3. RESULTS AND DISCUSSION

The snapshot of a drying channel array in figure 3 clearly shows that narrow channels dry faster. Figure 4 shows drying rates as a function of *1/w* (compare eq.1) at two RH values. The good match between measurement results and theoretical predictions proves the predominance of corner flow. Two phenomena are apparent. Firstly the drying rate at 92% RH is between 100 and 1000 times faster than drying by vapor diffusion (also shown), illustrating the importance of the corner flow effect. Secondly drying at the RHs of 43 and 92% is equally fast. The reason for this counterintuitive phenomenon is that there hardly exists an axial RH gradient in the channel in a corner flow-dominated drying process due to the low transport resistance of the corner flow path so that no dependence on external RH arises. The results of this study can be very useful for the design of micro heat-pipes [3] and also for clothing design. In both cases efficient wicking is of prime importance.

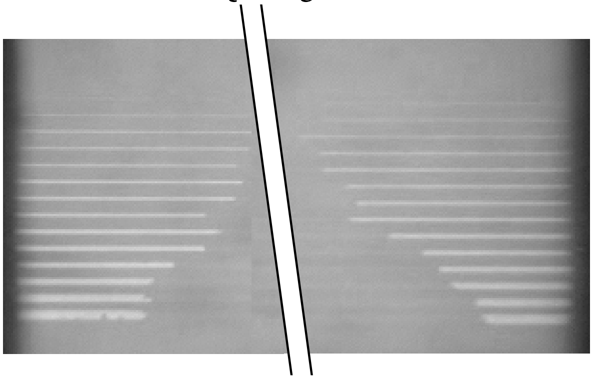

Figure 3 Snapshot taken 27 seconds into the drying of a channel array at a RH of 91.8%. Channel sections that have dried up appear white on the photo. The 4 mm long channels dry from both ends; the middle part of the array has been omitted for clear viewing.

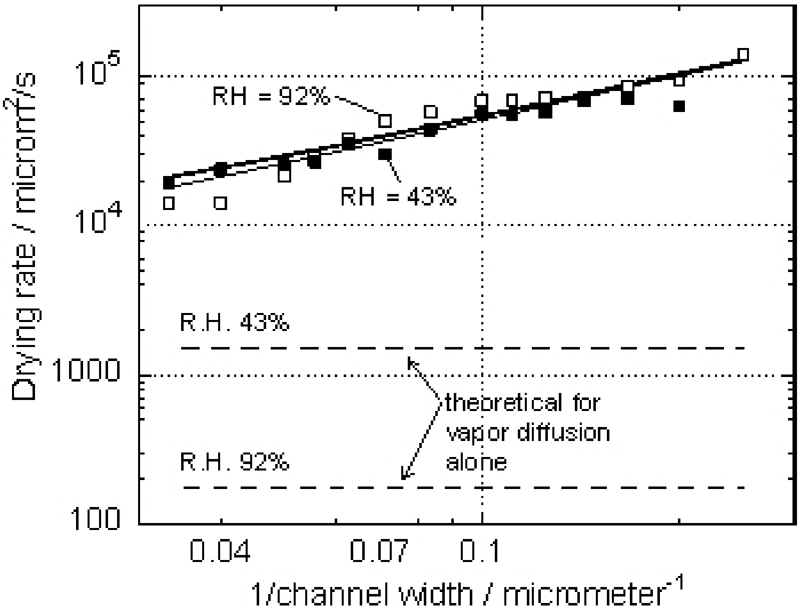

Figure 4 Measured drying rates (RH 43% and 92%) against reciprocal channel width and theoretically predicted curves (continuous lines bold 43%, thin 92%) using equation 1. The slope of the continuous lines indicates the width-dependent contribution of the corner flow. Dotted lines are the theoretical drying rates for drying by vapor diffusion alone.

ACKNOWLEDGEMENTS

This research was supported by the Dutch Ministry of Economic Affairs through a NanoImpuls grant. JE wishes to thank Sebastiaan Herber for his assistance with figure 1.

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