EXPERIMENTAL PINNING-DEPINNING MECHANISM OF THE CONTACT LINE ON PATTERNED SURFACES

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Abstract: We study the interface fluid-air of water in a patterned surface of a microchannel with a step. Our aim is to analyze how the advancement of the front is affected by local pinning-depinnig of the contact line between the fluid and the patterned surface. Microchannels with different patterns made of PDMS were fabricated in order to study the front behaviour. The interface moves forward due to a forced imbibition created by a water pressure on a reservoir at a known height. The fluid front is characterized by a constant velocity regime along the microchannel. We have observed that the pinning-depinning mechanism generates a local avalanche of the front, as well as it is concluded that this phenomenon produces an increase of the fluid velocity after the step. The front holds in a linear regime before and after the pattern. We also see that the avalanche effect is more relevant at low pressures or low velocity conditions.

I. INTRODUCTION

Interest in research of microfluidics has increased considerably in recent years [1]. The study of how a fluid that is restricted in a micrometer-sized channel behaves is mostly focused on the fields of bio-engineering, such as the study of blood pathologies. In order to be able to create applications in this field, it is necessary to first be able to characterize how a fluid such as water behaves in these devices.

As it is shown in Figure 1, we want to point out some studies that show what happens to water droplets when they meet a tip, inspired by nature forms such as pine needles or the geometries on a reptile footpad [2]. It is observed that when a drop of water is at an asymmetric or curved tip it adopts a preferential configuration towards the curved side [3]. Using this geometry in our favor we can have a global control of the transport to a privileged direction (the microchannel lenght), in addition to disadvantage the return of fluid backwards.

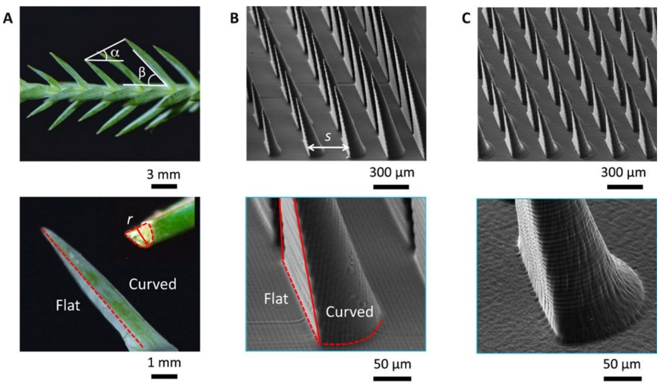

Figura 1: Geometry of pine needles and PNAS arrays used in the Janus pillars study [2].

Following this idea, we can create a device with a much simpler geometry but that keeps the idea of the tip shape where it can be pinned, and observe how for low pressure differences the hydrophobic interactions of the water front with the walls of the microchannel put the front close to the pinning point.

Our aim with this study is to analyze the behaviour of a Newtonian fluid front in a microchannel that presents a step pattern in one of the walls. Under these conditions the fluid will suffer a phenomenon called pinning-depinning, in which we will see how by the effect of the step a part of the fluid front is pinned and delays its flow until the other half of the front is advanced enough to depin . After this, it is noticeable an *avalanche* effect.

We have done experiments with different microchannels and tracked the position of the front in order to characterize the fluid behaviour under this concrete conditions.

II. MICROCHANNEL FABRICATION

The microchannels used throughout the development of this study have been fabricated in the *Clean Room* of the UB Physics faculty with the technique of Optical Lithography.

There are several methodologies that can be used to manufacture this microchannels, but in our case we use the lithography because of its simplicity, it is a very cheap technique, and we can produce it for our own in the laboratory. Besides, it is the most suitable technique to use with the material we need for our microchannels.

Optical Lithography is used for a wide variety of applications with different materials depending on specific needs (for example, metals such as silicon or aluminum are used to make microchips with this method).

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For the mold fabrication it is used a glass substrate. First, we deposit the photoresist that will work as a mask to print the channel pattern. In our case we use Ordyl, which is a $55\mu m$ thin layer negative photoresist. We put the mask designed with libreCAD that we want to use on the photoresist and we give it a 20s exposure with a UV lamp . The pattern is exposed by the mask in order to polymerize their bonds with the supplied energy, while the covered photoresist remains as at the begining. A developer is applied to remove the covered parts.

The microchannel is made of an hydrofobic silicone, PDMS (polydimetilsiloxane) in a ratio of 1:10 with the activating agent. The mixture is poured uniformly on the mold and put it on the hotplate for 1 hour so that it solidifies. Finally, the channel must be glued to a glass substrate. This process is done in a plasma cleaner where the surfaces get ionized so when they come in contact they get strongly bonded.

Two microchannels were used for the experiment with dimensions of $w = 300\ \mu m$ (width) and $l_c = 4{,}0cm$ (large). The first one has a heigh of $b = 50\ \mu m$ and a step of $50\mu m$x$50\mu m$. The second has $b = 100\ \mu m$ and a step of ax$c = 50\mu m$x$100\mu m$, see Figure 2 (a).

III. EXPERIMENTAL SET-UP

The experimental measures we have used in this study have been taken entirely in the microfluidics laboratory on the 6th floor of the UB Physics faculty.

The laboratory is equipped with a non-inverted microscope Optika B350 with 4x, 10x and 20x objectives; connected to a Chronos 1.4 High Speed Camera recording captures 1280x1024 @ 1057fps, and up to 38500fps at lower resolution. For our experiments we used a range of frames per second from 500 to 5000, depending on whether we needed a more general image (low fps) or many experimental points (high fps).

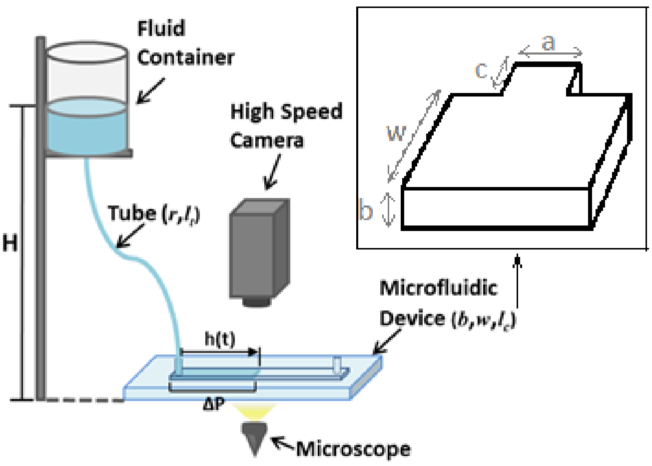


Figura 2: Schematic representation (a) and realimage (b) of the experimental set-up in the laboratory [4].

As explained in the manufacturing section, we have a microchannel with the bottom surface made of glass and the lateral and top surfaces made of PDMS. We can observe either way from the top or the bottom interface since it has been shown the waterfront behavior of the fluid is the same for both materials, which is one of the main reasons for using PDMS.

To make the water flow through the channel we used various techniques: injection or suction pump at constant pressure, pressure controlled by a column of fluid in a reservoir or sinusoidal pressure with a piezoelectric.

A qualitative study of the behavior was performed with the piezoelectric or with a Mitos Fluika Pressure Pump that provides pressurized air of up to $5 \cdot 10^4\ Pa$ above atmospheric pressure and controlled with its own software. For the quantitative study we use the system shown in Figure 2, where we control the pressure we want from the height of the reservoir, using a range of $H = 0.20$ to $0.40\ m$. The water column is connected to the microchannel with a to a microtube of biocompatible material with uniform internal circular cross-section of radius $d = 0.125\ \mu m$ and length $l_t = 0.610m$.

IV. EXPERIMENT AND DATA ANALYSIS

The experiment is based on tracking the position of the water-air interface as a function of time. In order to obtain those data sets we are going to characterize the average position of all the points of the waterfront for each frame and thus be able to fins the speed, see Equation (1).

$$\bar{h}(t) = \frac{1}{N}\sum_{i=1}^{N} h_i(x,t) \qquad (1)$$

The pinning-depinning process is shown in Figure 3 We will be also interested in finding the evolution of the point of the waterfront that is closest to the wall of the microchannel where it finds the step. We will compare this with a midpoint of the front and with one of the the other lateral surface.

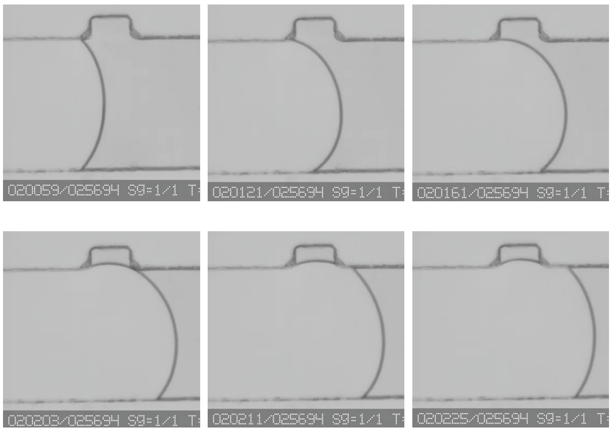


Figura 3: Front evolution during the step.

We use a 10x lens if we want a general shot so that we can characterize the front before, during and after passing the step. We use the 20x lens to see in more detail the pinning-depinning phenomenon that takes place when passing through this channel geometry.

Values of pressure must be high enough to beat the capillary pressure on the front so the fluid can get in the channel, but at the same time we should not use too high pressures as we will have to use a very high value of frames per second.

With the conditions in which the experiments have been done the mean position of the front be estimated according to the following relation [5]:

$$\bar{h}(t) \propto t^{\nu} \tag{2}$$

where the factor ν is yet to be determined between $\nu = \frac{1}{2}$, for long times holding the Washburn regime or $\nu = 1$ for short times.
Take into account that these relations are valid on a perfectly studied regime in a uniform channel, so the behavior during the step could be different, but for now we can take it as a good first approximation.

The data has been processed from a basic Matlab code that allows us to calculate each position along the fluid front in all frames. This program binaries one frame and calculates the minimum and maximum pixel positions of each front position; that is, it finds the position of the points at the air interface and the part of the liquid. We calculate an average of these two data and acquire an output of each position in each frame of the video, $h_i(x,t)$. The design of the code allows us to visualize the analysis frame by frame to be able to have a notion that it is being processed correctly.

From a change of conversion from pixels to meters depending on the lens used we finally get a complete characterization of the fluid path through the channel.

V. RESULTS AND DISCUSSION

A. Qualitative study

A qualitative study of the behaviour of the rare event [6] of the fluid front in the pinning-depinning process is showed below for a specific experiment with the 50x50 channel at H = 22 cm recorded with 1000fps.

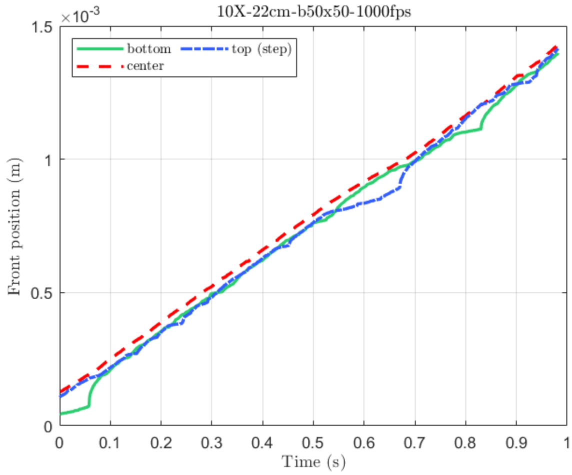


Figura 4: Position of three different fluid front points versus time.

The three points presented in Figure 4 shown the different behaviours the front can acquire. First, a middle point of the water-air interface is presented, the one corresponding to the red line. As it was expected, this point always has a further position, as we are pushing the fluid. Moreover, it maintains a stable relation in time, as it does not present irregularities along the path.

We now focus on the point of our interest: the closest point to the interface that presents the pattern we are studying, the blue line. About halfway through the front along the channel we have a non linear behaviour. The forehead point begins to slow down and suddenly jumps into a much more advanced position in a very short time: this is what we call the *avalanche* phenomenon. Then it returns to the linear function and gets closer to the other points.

With the representation of the bottom point without a step we want to highlight other observations: although the evolution of the position as a function of time is much more stable, several points in the graphs present some deviation that could also be attributed to avalanche effect, without existence of a step. Specifically, around 2 seconds we can clearly appreciate another pinning-depinnig mechanism in the green line due to a real imperfection in the bottom surface. We see that the front is very susceptible to any kind of surface defect that can be found on the PDMS walls of the channel. (We observe this phenomenon on both walls).

B. Quantitative Study

In this section we get into a more quantitative analysis of the phenomenon study. We will represent the contact line position of the front along the entire microchannel in order to study if the slope modifies in the different sections.

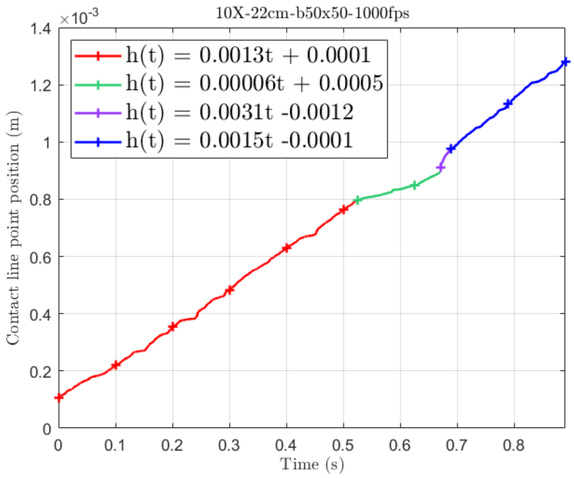


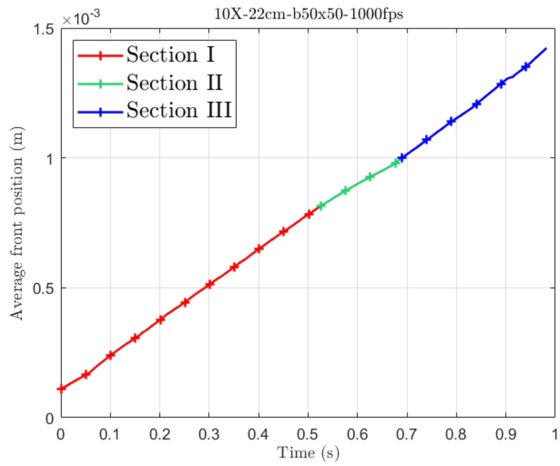
Figura 5: Average position of the contact line position versus time. Differentiated segments for the fluid front before the step (red), pinning-depinning (green), avalanche (purple) and after the step (blue).

In Figure 5, we plot the position of the contact line defined as h_c. The flow is splited in three main sections: from the beginning to the instant where the interface sticks to the step, the whole path over the step and from the moment the front returns to the original shape to the end of the microchannel. We also track the avalanche process until it gets the initial behaviour again.
Using a linear approach, the contact point behaves like:

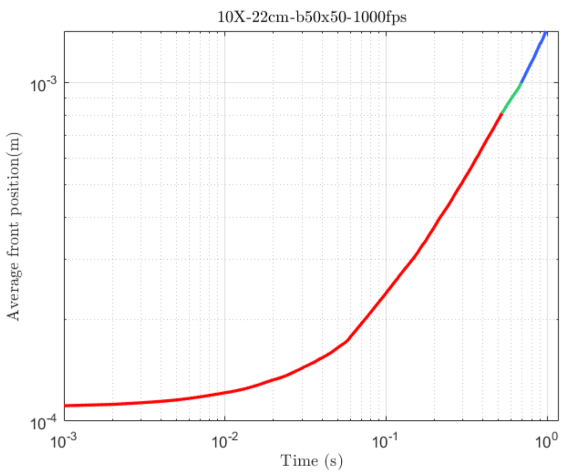
$$h_c(t) = v \cdot t + h_o \tag{3}$$

Therefore, we can get the velocities for each section value from the linear regression slope as $v_o \equiv$ *inicitial velocity*, $v_{p-d} \equiv$ *velocity during pinning-depinning* $v_a \equiv$ *velocity in the avalanche* and $v_f \equiv$ *final velocity*. Thus, we extract a velocity relation that follows $v_{avalanche} > v_f \approx v_o >> v_{p-d}$, so it is concluded that the flow almost stops its movement in the contact line during the pinning-depinning mechanism. In the avalanche we detect a much higher velocity and, although the final velocity gets closer to the initial one, an increase of the speed is detected.

Now we want to study if the effects of the estimated velocities do have a global repercussion. Due to the high number of frames per second with which we recorded these videos (in the specific case above we are at 1000fps), we obtain a sufficient number of data to be able to determine with good accuracy a curve fit for each section studied (OriginPro is used for the fitting). Since we are



(a) Linear



(b) Logarithmic

Figura 6: Average position of the front versus time for the three main sections.

studying the relation between the position and the time following the Eq (2), we propose the following curve:

$$\bar{h}(t) = \alpha \cdot t^{\nu} + \beta \tag{4}$$

Values for α, ν and β are collected in Table I for the three sections.

If we analyze the results obtained we can asume linear regime for the sections I and III, whereas in section II we can not conclude wether the regime is linear with time during the step. In the linear regime is easy to see then, that the velocity is extracted from the slope value α. The pinning-depinning mechanism of the contact line does have a global effect on the front behaviour as we can clearly differentiate the behaviour on the three sections established.

Other experiments with several heighs and step dimensions have been carried out in order to have mor references, see Table II.

Value	**Section I**
$\alpha(m/s)$	$(1{,}365 \pm 0{,}004) \cdot 10^{-3}$
ν	$(0{,}995 \pm 0{,}001)$
$\beta(m)$	$(1{,}013 \pm 0{,}004) \cdot 10^{-4}$
Value	**Section II**
$\alpha(m/s)$	$(1{,}064 \pm 0{,}009) \cdot 10^{-3}$
ν	$(0{,}658 \pm 0{,}005)$
$\beta(m)$	$(9{,}665 \pm 0{,}004) \cdot 10^{-4}$
Value	**Section III**
$\alpha(m/s)$	$(1{,}430 \pm 0{,}007) \cdot 10^{-3}$
ν	$(1{,}109 \pm 0{,}009)$
$\beta(m)$	$(4{,}019 \pm 0{,}003) \cdot 10^{-5}$

Tabla I: Fitting values for Eq 4 of the average front before (I), during (II) and after (III) the step.

Experiments	v_o **(mm/s)**	v_f **(mm/s)**
50x50,0.22	13.65	14.30
50x50,0.27	9.04	9.56
50x50,0.23	5.04	5.55
50x50, 0.21	4.30	5.05
50x100,0.39	3.13	3.98
50x100,0.20	2.25	6.03

Tabla II: Initial and final front velocities for six different experiments. In the first column it is presented the microchannel dimensions and the value of height H in meters.

It is observed from the results of the different experiments that after the avalanche in linear regime the velocity it is always accelerated. Furthermore, we can also see that this velocity growth is greater as we reduce the initial velocity of the fluid.

VI. CONCLUSIONS AND FURTHER STUDIES

A fluid confined in a microchannel with a step pattern subjected to force imbibition has an avalanche at the contact line due to the pinning-depinning mechanism. This contact line first presents a linear behavior with a specific velocity before it gets to the defect, then it reduces its movement until it almost stop and then gets a very abrupt advance, and finally returns to linear behavior at a slightly higher speed than it initially had.

Focusing our attention on the average behavior of the forehead we see that the situation described above has global effects on fluid velocity. It has been shown that the front maintains a linear relation of mean front position as a function of time before and after the pinning-depinning mechanism, and more specifically the velocity that the front finally acquires is higher than it initially was.

The avalanche phenomenon is accentuated with low pressures that generate greater susceptibility to defects (caused or natural) that can be found on the surface of the microchannel.

With these observations we still have open questions to solve about this phenomenon, which we want to address in future experiments. Once we see that there is indeed a change of speeds, we will want to study in more detail how the pressure parameters and dimensions of the channel affect.

Finally, we will also have to see how this whole experimental study fits with the proposed computational model based on simulations; and from there be able to find a theoretical model that determines the phenomenon.

Acknowledgments

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