Open-Surface Microfluidics

J. Berthier, K.A. Brakke[2], E.P. Furlani[3,4], I.H.Karampelas[3], G. Delapierre[1]

[1] Department of Biotechnology, CEA-Leti, 17 avenue des Martyrs, 38054, Grenoble, France
[2] Department of Mathematics, Susquehanna University, Selinsgrove, PA
[3] Department of Electrical Engineering, University at Buffalo, SUNY, Buffalo, NY
[4] Department of Chemical and Biological Engineering, University at Buffalo, SUNY, Buffalo, NY
Corresponding author: jean.berthier@cea.fr

ABSTRACT

Open-surface microfluidics has emerged recently in the biotechnological domain. It combines the advantages of capillary actuation, which does not require pumps or syringes to move the fluids, with low-cost fabrication, user-friendliness, portability and telemedicine compatibility.

In this work, we review the theoretical developments of spontaneous capillary flows in open microgrooves, and we present promising applications for point-of-care (POC) and home-care systems as well as cell culture systems.

Keywords: spontaneous capillary flow, capillary force, microgroove, suspended channels, Concus-Finn filament.

1 INTRODUCTION

Open-surface fluidics started in the mid 1900's, triggered by space applications [1]. In space, gravity is negligible and surface tension and capillarity are the dominant forces [2,3] (figure 1A). Later focus has been on the capillary flow of liquid solder in microgooves for microelectronic applications [4-6] (figure 1B).

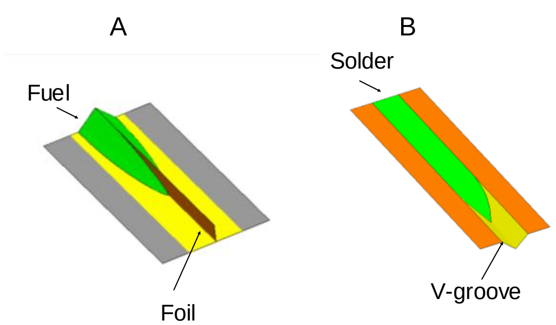

Figure 1. A: foils for the transport of fuel in spacecraft; B: liquid solder advancing in a V-groove, before solidification (both images obtained with Surface Evolver [7]).

More recently, applications of open-surface microfluidics have reached the domain of biotechnology. The picture is similar to space applications, because at micro and nano-scales gravity is negligible compared to surface tension and capillary forces. The recent developments of open-surface microfluidics (OSM) for biotechnology are motivated by the development of point-of-care (POC) and home-care systems [8,9].

From a biotechnological standpoint, the advantages of capillary systems are (1) low cost due to easy and fast fabrication, (2) portability ensured by the capillary actuation of the fluids, which does not necessitate bulky equipment such as pumps, or external energy sources, such as electric sources, (3) user-friendliness due to the simplicity of the device, (4) compatibility with telemedicine [10,11].

Open systems bring the additional advantages of accessibility—ink jetting or pipetting can be performed if necessary and optical observation is easy—and the ability to eliminate air bubbles, which are a serious drawback in many closed systems. All these aspects contribute to make open capillary systems an interesting choice for POC and home-care systems, under the condition that the limit of detection (LOD) and scalability are sufficient. Two different paths have been taken: the most popular is the paper-based approach where "lateral flow" is used to wick a matrix of cellulose fibers [12]. The paper matrix is used as a "wicking channel" to transport the fluids and reagents. Two different sub-categories can be distinguished: paper stripes, where a 1D capillary flow passes through regions loaded with the reagents, and 2D devices, where different reaction zones are implemented.

The second path—which is the subject of this work—is just in its infancy and makes use of grooves to move the fluids and transport the analytes [13] (figure 2).

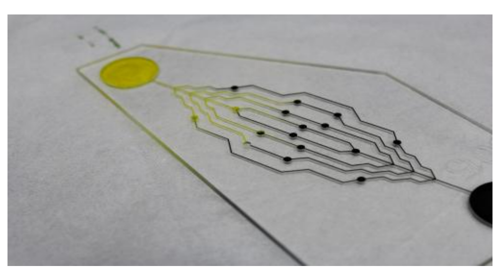

Figure 2. Sketch of an open U-groove network.

In this text, we focus on the capillary flows in open-groove systems. We present the theory of spontaneous capillary flows in general geometric morphologies, which is based on the Gibbs free energy [14,15]. We also investigate a new, interesting geometry, that of suspended micro-channels, i.e. where flows use surface tension to fill and maintain a fluid in microscale structures devoid of a ceiling and floor [16].

The spontaneous capillary flow (SCF) onset and dynamic aspects are investigated in all these different geometries. Recent applications are reported and analyzed.

2 SCF THEORY

Spontaneous capillary flow occurs when the energy reduction from wetting walls outweighs the energy increase from extending the free surface. Using Gibbs thermodynamic equation, it has been shown that the general condition for SCF in composite-wall and air systems is that the generalized Cassie angle must be less than 90° [15]. Let us recall that the generalized Cassie angle θ^* is the average contact angle defined in the appropriate way, i.e

$$\cos\theta^* = \sum_k \left(\cos\theta_k \; f_k\right), \tag{1}$$

where θ_k are the Young contact angles with each component k (including air) and f_k the areal fractions of each component k in a cross section of the flow (figure 3). Note that the virtual contact angle with air is 180°. In the case where the walls are composed of a single material (with the same functionalization), relation (1) reduces to

$$\frac{p_F}{p_W} < \cos\theta \;, \tag{2}$$

where p_F and p_W are respectively the free—in contact with air—and wetted—in contact with wall—perimeters in a cross section of the channel.

3 SCF IN U- AND V-GROOVES

It is a common observation that microscopic grooves etched in a solid plate facilitate capillary flows [13,17].

Applying (2) to a rectangular U-groove yields the condition

$$q = \frac{w}{d} < \frac{2\cos\theta}{1-\cos\theta}, \tag{3}$$

where w is the slot width and d its depth. Relation (3) indicates that, for a given contact angle θ, the aspect ratio $q=w/d$ is limited.

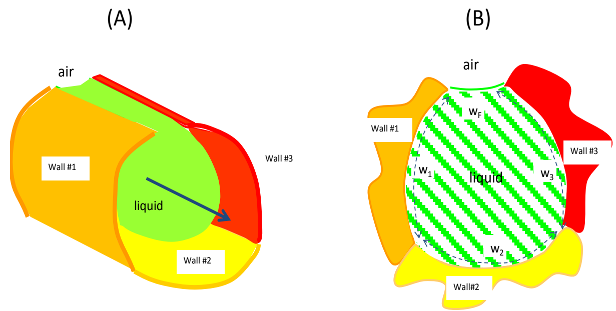

Figure 3. Cross-section of a partly open composite microchannel: the lengths w_i stand for the wetted perimeters and w_F for free perimeter. The areal fractions are $f_i = w_i \Big/ \left(\sum_i w_i + w_F\right)$ and $f_F = w_F \Big/ \left(\sum_i w_i + w_F\right)$.

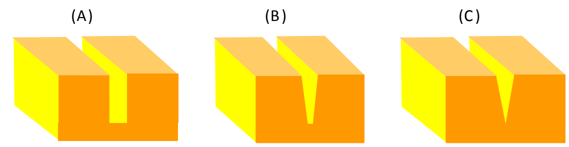

Figure 4. Different shapes of grooves: (A) Rectangular (U-shape), (B) trapezoidal, (C) triangular (V-shape).

In other words, the height of the walls d must not be too small compared to the channel width w.

In the case of a V-groove of geometrical angle 2α, relation (2) yields

$$\frac{w}{2d} = \frac{w}{w/\sin\alpha} = \sin\alpha < \cos\theta \;. \tag{4}$$

This relation can be rewritten as

$$\theta < \frac{\pi}{2} - \alpha \;. \tag{5}$$

Relation (5) is the Concus-Finn relation [1]. It indicates that a filament will progress indefinitely in the groove if (5) is satisfied, else no capillary flow will occur. Note that in all cases, SCF only depends on the geometrical characteristic dimensions and the contact angle.

On the other hand, the dynamics of the flow depends also on the physical properties of the liquid, and on the surface tension of the liquid. The dynamics of capillary flows inside V- and U-grooves has been reported in the literature [2,4-6,18]. A comparison of the different dynamics depending on the geometrical characteristics of the channel is presented in a sister paper of the 2014 Nanotech conference [19].

It is shown in the literature that inertia can usually be neglected in microchannels. In the case of a V-groove of semi-angle α, it has been shown that the square of the velocity of the flow is

$$V = \frac{\gamma}{\mu}\frac{h}{z(t)} g(\alpha,\theta) = \frac{\gamma}{\mu}\frac{h}{z(t)}\frac{(\cos\theta - \cos\alpha)}{4\pi\sin\alpha} \quad . \qquad (6)$$

In the case of a U-groove, we can express the capillary and friction forces by

$$F_{cap} = p_W\,\gamma\cos\theta - p_F\,\gamma \quad , \qquad (7)$$

$$F_{drag} = 6\,\mu\frac{V}{w}z(t)\,(2\,h) + 6\,\mu\frac{V}{h}z(t)\,w \quad . \qquad (8)$$

Hence, using the no-inertia hypothesis $F_{cap} = F_{drag}$, and introducing the aspect ratio $q=w/h$, we obtain

$$V = \frac{\gamma}{\mu}\frac{h}{z(t)}\frac{[(q+2)\cos\theta - q]}{3\left(\frac{2}{q}+q\right)} \quad , \qquad (9)$$

an expression that has the same form as (6), with a different geometrical function. Expression (9) has been checked with success against experimental data (figure 5), and using the FLOW3D numerical software.

4 SUSPENDED MICROFLUIDICS

A suspended microflow is a flow that uses capillary forces and surface tension to fill and maintain a fluid in microscale structures devoid of a ceiling and floor (figure 6). These flows have the advantage to be accessible on both sides, from above and from below.

A criterion for SCF in such geometry is deduced from the theory—relation (2)—and was checked with Surface Evolver. If we consider a suspended channel with vertical, parallel walls, where w is the distance between the walls and h the height of the walls, the condition for the establishment of SCF is then

$$q = \frac{w}{h} < \cos\theta \quad . \qquad (10)$$

The dynamics of this kind of microflow is derived in the same manner as for U- and V-grooves (figure 6), and we find

$$V = \frac{\gamma}{\mu}\frac{h}{z(t)}\frac{[q(\cos\theta - q)]}{3} \qquad (11)$$

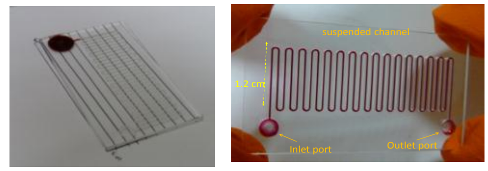

Figure 5. Left: SCF in a winding U-groove channel; right: SCF in a suspended channel

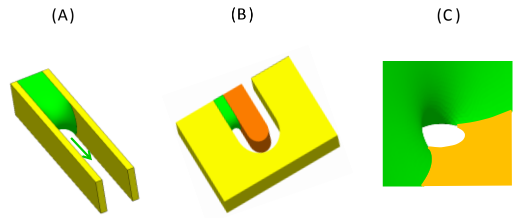

Figure 6. Three different morphologies of suspended microfluidics.

5 APPLICATIONS TO BIOTECHNOLOGY

As stated in the introduction, open capillary systems are well suited for POC and home-care devices, and for biologic applications.

Capillary flow in open sharp V-grooves has been used to design portable blood testing systems for the determination of the time for coagulation [20] (figure 7). In this design a sharp V-groove is used to transport whole blood from a finger prick to a reservoir (in less than 0.2 seconds). A “speckle” method is then used to determine the coagulation time.

Suspended microflows of polymeric solutions above circular apertures have been used to form µDOTS for cell culture [16] (figure 8). A liquid polymeric solution is first moved in a U-channel pierced with cylindrical holes, filling the holes. The liquid is aspirated, leaving the holes filled. Upon polymerization, the holes constitute collagen µDOTS that can be used for cellular behavior analysis.

Using the same idea of first liquid, then gelled polymers, generation of interstitial and intramural flows within a three dimensional (3D) microenvironment has been set up for cellular behavior studies [21]. The principle is to have liquid collagen walls form between ridges, and then gel these walls to obtain porous separations.

6 CONCLUSION AND PERSPECTIVES

The aim of this text was to review the theory and development of open-surface microfluidics (OSM) and to show its potential in the domain of diagnostics and cell culture.

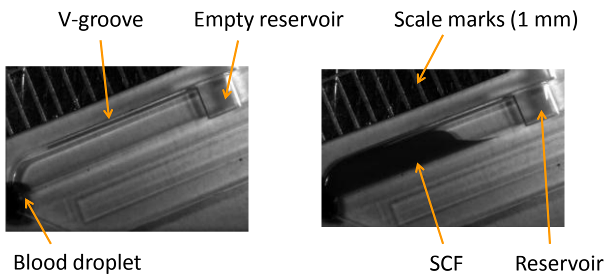

Figure 7. Whole blood SCF in a sharp V-groove.

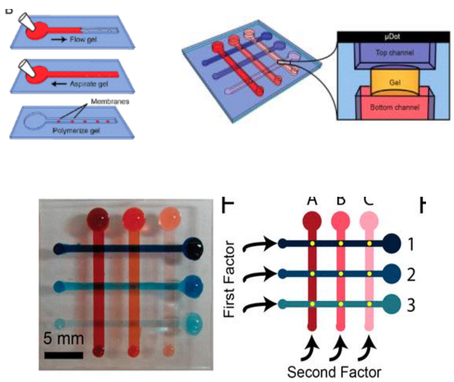

Figure 8. Top: formation of a matrix of collagen µDOTS by suspended microflow. Bottom: liquids with different concentrations flow in the top and bottom channels at differenet concentrations.

REFERENCES

[1] P. Concus and R. Finn, On the behavior of a capillary surface in a wedge, PNAS **63** (2), 292-299, 1969.

[2] M.M. Weislogel, S. Lichter, Capillary flow in interior corners, Journal of Fluid Mechanics, **373**, 349-378, 1998.

[3] M.M. Weislogel, Capillary flow in interior corners: The infinite column, Physics of fluids, **13** (11), 3101-3107, 2001.

[4] R.R.Rye, F.G. Yost, Wetting kinetics in surface capillary groove,s Langmuir, **12**, 4625-2627, 1996.

[5] F.G. Yost, R.R. Rye, J.A. Mann, Solder wetting kinetics in narrow V-grooves, Acta Materialia, **45**, 5337-5345, 1997.

[6] L.A. Romero, F.G. Yost, Flow in an open channel capillary Journal of Fluid Mechanics, **322**, 109-129, 1996.

[7] K. Brakke, The Surface Evolver, Experimental Mathematics **1**(2),141-165, 1992.

[8] G.V. Kaigala, R.D. Lovchik, E. Delamarche, Microfluidics in the open space for performing local chemistries on biological interfaces, Angew. Chem. **51**, 11224-11240, 2012.

[9] J. Berthier, From microfluidics for biotechnology to biomicrofluidics, 2013 Nanotech Conference, 13-17 May 2013, Washington DC.

[10] L. Gervais and E. Delamarche, Toward one-step point-of-care immunodiagnostics using capillary-driven microfluidics and PDMS substrates, Lab Chip, **9**, 3330-3337, 2009.

[11] A.W. Martinez, S.T. Phillips, E. Carrilho, S.W. Thomas, H. Sindi, G.M. Whitesides, Simple telemedicine for developing regions: camera phones and paper-based microfluidic devices for real-time, off-site diagnosis, Analytical Chemistry, **80**, 3699, 2008.

[12] P. Yager; T. Edwards, E. Fu, K. Helton, K. Nelson, M. R. Tam & B. H. Weig, Microfluidic diagnostic technologies for global public health, Nature, **442** (7101): 412–418, 2006.

[13] J. Berthier, K. Brakke, The Physics of Microdroplets, Scrivener-Wiley Publishing, May 2012.

[14] J.W. Gibbs. Transactions of the Connecticut Academy of Arts and Sciences **, 2**, 382-404, 1873.

[15] J. Berthier, K. Brakke, E. Berthier, A general condition for spontaneous capillary flow in uniform cross-section microchannels, Microfluid. Nanofluid. Journal, DOI 10.1007/s10404-013-1270-1, 2013.

[16] B.P. Casavant, E. Berthier, A.B. Theberge, J. Berthier, S.I. Montanez-Sauri, L.L. Bischel, K. Brakke, C.J. Hedman, W. Bushman, N.P. Keller, D.J. Beebe. Suspended microfluidics, PNAS **110** (25), 10111-10116, 2013.

[17] L. Liu, A.M. Jacobi, D. Chvedov, A surface embossing technique to greate micro-grooves on an aluminum fin stock for drainage enhancement, J. Micromech. Microeng. **19**, 035026, 2009.

[18] F. F. Ouali, G. McHale, H. Javed, C. Trabi, N. J. Shirtcliffe, M. I. Newton, Wetting considerations in capillary rise and imbibition in closed square tubes and open rectangular cross-section channels, Microfluid Nanofluid., **15**, 309-326, 2013.

[19] J. Berthier, N. Villard, A-G Bourdat, C.Pudda, G. Nonglaton, F. Boizot, C. Fontelaye, G. Delapierre, On the velocity of spontaneous capillary flows in confined and open microchannels, Nanotech Conference, 15-19 June 2014, Washington DC.

[20] P. Pouteau, J. Berthier, V. Poher, Dispositif de prélèvement d'un échantillon de liquide par capillarité et procédé d'analyse associé. French Patent, March 7, 2013, n° 13 52050.

[21] Chih-kuan Tung, O. Krupa,E. Apaydin, Jr-Jiun Liou, A. Diaz-Santana, Beum Jun Kima and Mingming Wu, A contact line pinning based microfluidic platform for modelling physiological flows, Lab Chip, **13**, 3876–3885, 2013.