Open Microfluidics
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Jean Berthier
CEA/LETI, University of Grenoble, France

Kenneth A. Brakke
Department of Mathematical Sciences, Susquehanna University, USA

and

Erwin Berthier
Department of Biomedical Engineering, University of Wisconsin Madison, USA
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Preface

In 2012, Ken and Jean produced the book *The Physics of Microdroplets*. The aim of the book was to present the behavior of droplets in the many different configurations that occur in microsystems. It encompassed the behavior of sessile droplets on inhomogeneous substrates, droplets electrically actuated, interaction of droplets with interfaces, droplets in two-phase flows, and the use of droplets to align objects. The book was not strictly a story of droplets, as an introductory chapter to “open microfluidics” was also included. At that time, microflows with open boundaries, i.e. liquid-air interfaces, were starting to interest scientists working in space exploration as well as in biotechnology, biology and energy domains.

The interest in open microflows has continued to grow. Biologists especially have found that the accessibility provided by flow with open boundaries was extremely useful. Reagents can be easily added using a pipette—the fundamental tool of biologists—and fluid can be retrieved the same way. For biotechnological uses, open systems have the great advantage of simplicity of fabrication: they can be easily milled or molded, and they can be assembled together. They are also compatible with the new techniques of 3D printing. This simplicity is associated with low cost, which is required for the development of point-of-care and home-care devices—devices that can be used directly by a patient at home or at the doctor’s office. Open systems can also be straightforwardly converted into closed or partly closed systems by covering with thin plastic films, now currently available commercially, bringing a new versatility to microfluidic devices. From an energy standpoint, open interfaces allow for evaporation, and so cooling of microsystems can be easily performed using open microflows. Finally, open microfluidics, or open fluidics, is omnipresent in space applications where weight is the enemy: the removal of solid channel walls is a definite advantage.

Hence, using the same methodology as that of our first book, we decided that a continuation we call “open microfluidics” was opportune, due to the fast developments of this type of microfluidics. Erwin joined us in this enterprise, bringing the experience of a developer and pioneer of “suspended microfluidics”, a particular form of open microfluidics.

Due to the openness of some flow boundaries, the driving pressure must be small or even zero, else the fluid would overflow, and capillarity is the basis of the actuation of the fluids in open microfluidics. Open microfluidics is indissolubly linked to capillarity, as will appear in the following chapters.

In this new book, we tried to merge theoretical developments, numerical approaches—principally with the software Surface Evolver, stretching its application with care to microflows dominated by surface tension—and experimental examples, in order to give the reader the widest possible view of “open microfluidics”.

In the spirit of continuity of our approach with that of the previous book, we are happy that our former publisher Martin Scrivener continued to have confidence in us and the book.
The Evolver files corresponding to the examples and problems of this book are available for the reader at the internet address http://www.susqu.edu/brakke/openmicrofluidics.

We hope that our work will be useful to boost the developments of microfluidic systems and that this book will find an echo in the micro and nanotechnology world.

Jean Berthier, CEA-Leti, University of Grenoble, France
Kenneth A. Brakke, Susquehanna University, PA, USA
Erwin Berthier, Department of Biomedical Engineering,
University of Wisconsin Madison,
USA
Online Materials

Readers of this book are entitled to access all the Surface Evolver datafiles used in production of this book at http://www.susqu.edu/brakke/openmicrofluidics. There are also several animations, and an interactive app that does the phase diagrams in chapter 8.
Introduction

Open Microfluidics

Microfluidics is a relatively new scientific domain. Nevertheless its evolution has been extremely fast. Even if solutions for microelectronics [1-4] and outer space [5-8] have contributed to the development of microfluidics since the mid-1950s, it is now mainly biotechnology that boosts microfluidics and contributes to making it a growing scientific domain.

The goal of biotechnology is the fabrication of highly sophisticated tools to assist biologists in their research, automate and increase the efficiency of biology and medicine, and furnish solutions for the discovery of new drugs in pharmacology. At its beginning, biotechnology followed an engineering approach, due to the necessary physical development of the techniques. Progressively it has shifted to a biology-oriented field, in order to be closer to the needs of biology and medicine. [9].

These tools have first targeted with success genomics and DNA recognition. For example, many different solutions for sequencing DNA and biorecognition have been developed [10-14].
Figure 1 Biotechnology is a composite science in which microfluidics is a fundamental subdomain.

Figure 2 The main categories of microfluidics and their applications. Inertial microfluidics [97], reprinted with permission ©2008 ACS; paper-based microfluidics, reprinted with permission by Albert Folch, University of Washington, and from [96], reprinted with permission ©2011 ACS; rail based microfluidics [93], reprinted with permission ©2005 ACS; suspended microfluidics [74], reprinted with permission ©2013 PNAS; digital microfluidics, two phase flows and encapsulation, courtesy CEA-Leti; emulsion [38], reprinted with permission ©2003 AIP.

flows are driven by pumps or syringes external to the chip itself and many different types of valves have been developed [28-30]. These devices are mostly used in laboratories, owing to the need of auxiliary external systems, such as pumps, multiple syringes systems, reservoirs,
etc. Systems based on closed microfluidics have had great success and accomplished many important achievements, such as massively parallel DNA amplification [31,32], and the study of stem cell behavior [33-35].

In order to further reduce sample and reagent volumes, it was found that droplets could be used as vessels to perform the desired processes. The term droplet microfluidics is used to characterize such systems. The volumes used in such systems can be very small, on the order of a few nanoliters. Two different approaches depending on the targeted applications have been followed: first, a two-phase approach where the sample and reagents (usually aqueous fluids) are transported by an immiscible fluid (usually an organic liquid, such as mineral oil) in a larger network [36-40]. Second, a digital microfluidic approach, where droplets are moved one by one or in parallel on a patterned substrate by electrical (electrowetting and EWOD) or acoustic (SAW) methods [41-45].

Recently, the need for portable systems has appeared. This need is linked to the development of point-of-care (POC) and home-care medicine, where user-friendly, portable, and low-cost systems can be used at the doctor’s office or directly by the patients themselves to monitor their health, or detect bacteria and viruses from a blood prick [46-50]. Contrary to the conventional microfluidic solutions presented above, the requirement for portability and low cost is associated to the development of passive or nearly passive solutions, where external auxiliary systems are absent, except perhaps the energy of a mobile phone or a compact transportable energy source. Obviously, capillarity is the solution for moving liquids under these conditions [51]. In a capillary solution, the energy required for the motion of the fluids is the surface energy of the walls, which is built in at the moment of fabrication, or by appropriate functionalization of the walls [46,52].

Such portable systems are well-adapted, for example, to blood monitoring [53,54]. Human blood contains a bounty of information on human health: from the numerous metabolites contained in the plasma, such as glucose, cholesterol, and thyroidal hormones, to the bacteria and viruses transported by blood cells, and circulating tumor cells characteristics of cancerous attack [55-58]. Moreover, cell count, coagulation time, hemoglobin and fibrinogen levels are of great importance for health monitoring [59,60].

Capillary flow in cylindrical tubes was first studied by Bell, Cameron, Lucas, Washburn and Rideal in the 1910s [61-64]. With the development of new biological solutions for point-of-care and home care systems, studies on capillary flows have seen a revival. The first capillary systems to have been developed are fully closed rectangular channels; new functionalities such as trigger valves and capillary pumps have been invented to enhance the potentialities of such devices [65-66].

Still more recently, it became apparent that direct accessibility to biological systems would be a great advantage [67]. Open systems, i.e. microfluidic systems with open boundaries, bring the advantages of accessibility: Addition of reagents, pipetting for the addition or retrieval of biologic liquids or objects, and human interventions on the system can then all be easily performed [52]. Also, optical observation is facilitated. Finally, these systems have the ability to eliminate air bubbles, which are a serious drawback in many closed systems. All these aspects contribute to making 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.

Let us cite the arguments of BioProbe [68]:

Probing biological systems locally in an open space can lead to new insight and breakthroughs. Living matter likes surfaces. Substrates that are functionalized for biological applications are increasingly used and also commercially available. Microfluidics should be able to interact with such substrates in the open space,
essentially in their native state, which will facilitate the study of biological samples. To succeed in these endeavors, microfluidics needs to eliminate one of their major constraints: the walls.

These arguments have led to the development of capillary systems where some boundaries are open, i.e. in contact with the surrounding air. The names of open microfluidics, or open-surface microfluidics, or open-space microfluidics have emerged.

In fact, the domain of open microfluidics covers many different situations. Open capillarity has many different aspects, from the propagation of capillary filaments in corners [5,6,69-71], to the spontaneous capillary flow in open U and V-grooves [71-73], to suspended capillary flows [74,75], and to paper-based and thread-based microfluidics [76-80]. A panel of the different open-surface microfluidic configurations is shown in figure 3. In this book, electrowetting, capillary self-alignment and capillary rise are not treated extensively, as they are already widely documented in the literature [81,82].

![Figure 3](image)

**Figure 3** The main categories of microfluidics and their applications.

The first chapter of this book is dedicated to the theoretical approach to spontaneous capillary flow (SCF). Using the Gibbs free energy [83], it is shown that the condition to obtain SCF in an open or closed, composite or not, flow channel is that the equivalent Cassie angle defined in a cross-section is less than 90°. It demonstrates that SCF occurrence depends only on the geometry and the contact angles [84]. Next, the dynamics of capillary flows are presented. It is shown that, except for a very small length at the channel entrance where inertial effects appear [85], the viscous regime defined by the Lucas-Washburn-Rideal (LWR) model can be transposed to arbitrary cross-sectional channels, if precautions are taken [62-64,86]. Finally, the question of the dynamic contact angle is investigated. It is shown that an advancing contact angle only concerns essentially the entrance to the capillary channel [87-89].

The second chapter presents an oft-encountered feature in modern capillary microsystems: capillary filaments. The physics of these filaments was first investigated by Concus and Finn [5,6] in the context of spacecraft studies. These filaments may form in sharp corners or in cracks, and can extend endlessly as long as there is liquid available [82]. In capillary systems, these filaments may flow alone, or with the bulk of the liquid [69-71]. The different flow regimes in rectangular open channels are presented. Next, it is shown that the SCF condition in
sharp V-grooves, deduced from the theory of the preceding chapter, reduces to the Concus-Finn condition [73,84]. Finally, the formation of filaments in different geometries is theoretically and numerically investigated.

Rectangular, open microchannels, for simplicity called U-grooves in this book, are probably the most common open microfluidic devices, due to their easy fabrication. It suffices to mill a plastic plate to obtain such channels. The study of spontaneous capillary flow in such channels is the subject of chapters 3 and 4. In chapter 3, the conditions for SCF in the geometry of U-grooves are presented. Different geometries are investigated: straight, turning U-grooves, and U-grooves of varying cross-section (figure 4).

Figure 4 Different geometries of U-grooves. A: SCF passing through multiple cylindrical chambers, from an inlet port (right) to an outlet port (left); B: parallel SCFs from an inlet port to multiple outlet ports; C: multiple microgrooves in parallel; D: winding U-groove with cylindrical wells; E: SCF filling of a cylindrical cavity; F: Concus-Finn filaments in an open cylinder; G: Concus-Finn filaments in a varying cross-section U-groove. Photographs: J. Berthier, N. Villard, D. Gossefin (CEA-Leti).

In chapter 4, dynamical considerations on the capillary flow in U-grooves are presented [72,90,91]. The concept of flow resistor is developed. It is shown that the concepts of trigger valves, capillary pumps, and flow resistor, transposed from closed capillary systems [65,66] to open channels, may still be valid if precautions are taken.

Suspended microfluidics has very recently appeared in the literature [74,75,92]. It is the subject of chapter 5. By definition, suspended microflows are flows in channels devoid of ceilings and floors. Spontaneous flow conditions for different types of suspended microflows are given. Suspended microfluidics brings additional accessibility to open biotechnological systems, and is the source of new applications. Especially, applications to suspended flows of liquid polymers are presented.

Chapter 6 presents new developments for rail-based microflows [93]. Rail-based microfluidics is, in principle, similar to suspended microfluidics. In such systems, the liquid flows between two horizontal rails, top and bottom, and the flow has open boundaries on both sides. At first sight, it is similar to suspended microfluidics, with a 90° rotation. However, it is very different from suspended microfluidics when considering the concepts of microfluidic networks. Such networks are not compatible with suspended geometries. SCF conditions in rail geometries are detailed in the chapter. Different rails morphologies are investigated.
Chapter 7 presents the development of paper-based microfluidics. Paper-based systems were first proposed long ago by Yagoda in the year 1937 [94]. They have recently seen a considerable revival with the developments of paper-strips and μPADs (micro paper-based analytical devices). Strips are narrow bands of cellulose fiber where the liquid wicks the fibers and progresses in one direction and where the reaction zones are regions placed perpendicularly to the flow (figure 5). μPADs are two-dimensional planar devices where reaction zones are placed at the extremity of branches [76]. It appears that the solutions provided by labs-on-paper are very promising and have a large scope of applications [95]. In this chapter the principles, designs, detection methods and fabrication processes of paper-based devices and labs-on-paper are presented.

The final chapter of the book, chapter 8, is dedicated to thread-based microfluidics. It is a very new domain, which has recently seen new developments [79,80]. The concept of thread-based microfluidics is the use of fibers to guide and transport liquids. The particular physics of fiber wicking is developed in the chapter, and applications to smart bandages are presented.

Figure 5 A: Sketch of paper strips. B: Photograph of a μPAD. From [98], reprinted with permission ©2014 Springer. C: Close up of a thread showing the fiber bundle. From [78], reprinted with permission ©2010 ACS.

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