Design Paradigms and Methodologies for Microfluidics

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ABSTRACT

This short review discusses some important issues related to design rules for microfluidic systems. The classes of solutions for distribution of fluidic functionalities, fluid transport and modeling having emerged in the past few years as well as the corresponding flow patterns are briefly introduced and evaluated. The overview suggests that in microfluidics generic components and designs such as in microelectronics are largely missing, however, there are a number of preferred solutions. Recently a trend towards two-phase microflows has emerged, with corresponding requirements for CFD methods for free-surface flow derived from that.

Keywords: microfluidics, design rules, flow patterns, fluid transport, simulation

1 INTRODUCTION

Microfluidics is one of the emerging technology areas which is expected to have a major economical impact. In that context, Lab-on-a-Chip and µTAS systems seem to be among the most promising applications. Miniaturized biological and biochemical analysis is expected to revolutionize fields such as medical diagnostics and pharmacological research and enable point-of-care and high-throughput operation.

However, compared with the forecasts published some years ago, the economic implementation of microfluidic technologies falls short of the expectations. Up to now, only a few applications have experienced a major dissipation, and real breakthroughs have been very rare. In contrast to that, microelectronics has shaken up the economy and many areas of everyday life in the past 30 years. The question arises why microfluidics has not yet experienced a similar development.

The success of microelectronics depends on a few key factors. One important aspect is that most microelectronic systems are based on a small number of generic components which are arranged to form complex circuits using a modular design principle. One of these generic components is the MOSFET device which is omnipresent in microelectronics. Another key factor is the availability of advanced circuit engineering methods based on elaborate design rules and simulation techniques. In brief, there exists a design paradigm which has been widely accepted.

The purpose of this short review is to illuminate the state of the art of design methodologies and concepts in microfluidics. By evaluating the development of the field in the past few years it should become evident if anything like a design paradigm for microfluidics has appeared on the horizon and which gaps still need to be closed. Since microfluidics has grown to a field of immense diversity by now, it is clearly not possible to cover all application areas, so the focus will mainly lie on the Lab-on-a-Chip field.

2 DISTRIBUTION OF FUNCTIONALITIES

In a Lab-on-a-Chip or µTAS system, there are a number of different tasks to fulfill, among others fluid transport, mixing, dosing and metering. There are two different concepts of implementing such fluidic functionalities: Either a system consists of a number of sub-units or components, each of which performs only one or a small number of fundamental tasks, or a system is essentially a multiplication of identical units which are able to perform all of the required functionalities. The first idea may be referred to as the modular, the second as the monolithic concept.

An example for the modular concept is shown in Fig. 1. The metal rack shown in the figure holds a number of microfluidic chips and peripheral components which are coupled to each other [1]. The system, developed at IMM, Mainz, is a small diagnostics lab capable of PCR amplification of DNA strands and the necessary sample preparation, and it comprises different fluidic components such as ferrofluid pumps, a diaphragm pump, and units for mixing and fluidic metering. This “chip-based lab” contains two levels of modularization: First, there is the chip level. Each chip contains a number of microchannels performing tasks such as fluid metering. Beyond the chip level there is the system level at which the chips themselves together with the fluidic peripherals form the modules.

A microfluidic system based on the monolithic concept is sketched in Fig. 2. An array of fluidic actuators forms the “stage” for the processing of small droplets [2]. The actuator array is capable of performing unit operations such as droplet creation, cutting, merging and transport.

Concrete realizations of the monolithic concept often make use of the electrowetting effect by which droplets can be moved via electric-field induced variations of the contact angle. In such a case the “stage” for droplet manipulation consists of an array of electrodes coated with a hydrophobic dielectric layer. Fig. 3 shows the mixing of two merged droplets on such an array induced by periodic motion [3].

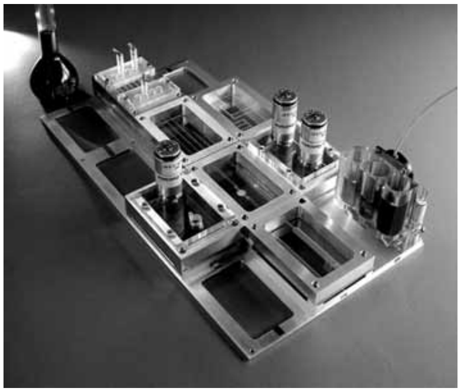

Figure 1: “Chip-based-Lab” containing a number of microfluidic polymer chips and fluidic peripherals.

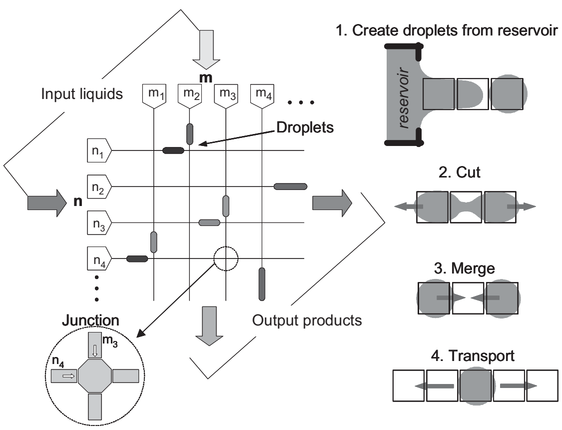

Figure 2: Sketch of a monolithic microfluidic system capable of performing a number of unit operations (reproduced with permission from [2], © 2003 IEEE).

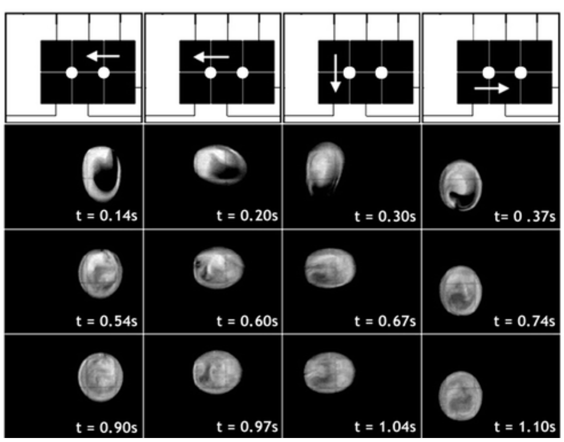

Figure 3: Time sequence of droplet mixing visualized by a fluorescent dye (reproduced from [3] by permission of the Royal Society of Chemistry).

An alternative monolithic concept for microfluidics makes use of acoustic streaming, i.e. the motion of liquids induced by surface-acoustic waves [4]. In that case piezoelectric transducers provide the driving force and allow for a controlled motion of droplets on a plane.

3 FLOW PATTERNS

The two basic choices of flow patterns for a microfluidic system are continuous flow and droplet-based flow, where under the latter also slug(plug)-flow patterns in microchannels are subsumed. The advantage of continuous flow is that its physics is fairly well understood and that the design of corresponding systems based on this understanding is comparatively straightforward. In contrast, droplet-based systems often exhibit “unexpected phenomena” in the sense that droplet transport is dictated by surface tension and wetting forces, the latter often giving rise to complex behavior such as contact angle hysteresis [5].

In spite of the simpler fluid handling continuous-flow systems possess a number of disadvantages. When a chemical species is dissolved in a liquid being transported through microchannels, the concentration field usually distributes over a considerable part of the channel network due to hydrodynamic dispersion. Thus, it is difficult to process small amounts of reagents in a well-defined manner. In addition to that, in continuous-flow systems very small liquid sample amounts require very small channels. Especially in the field of high-throughput screening the reduction of sample amounts and parallelization of the screening process are important issues. Owing to these disadvantages of continuous flow systems, droplet-based systems have attracted increasing attention in the past few years.

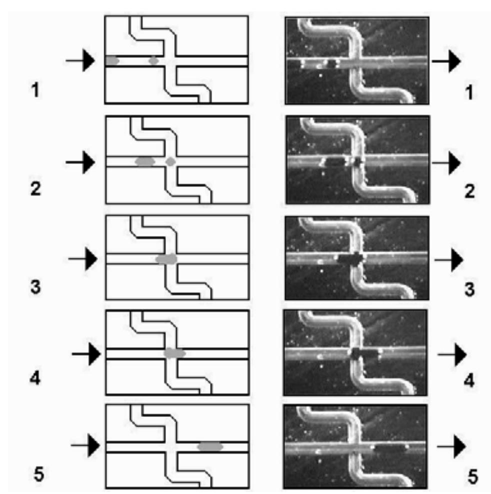

Figure 4: Merging of two droplets at a microchannel intersection (reproduced with permission from [6]).

Especially the monolithic concepts discussed in the previous section are designed for processing of small droplets. However, droplets or slugs are also an option for systems where the liquid transport occurs in microchannels. That way evaporation can be suppressed, but the degrees of freedom for droplet motion are reduced. The fluidic functionalities such as droplet merging and mixing can be realized at channel intersections using valving technology. Fig. 4 shows the transport and merging of two droplets in a microfluidic system developed at IPHT, Jena [6]. The recirculation flow induced in the resulting droplet when being transported through the channel promotes mixing.

4 FLUID TRANSPORT

Depending on whether the goal is to develop a completely miniaturized system or a microfluidic system embedded in a macroscopic periphery, the choices for the pumping technology may be different. In the former case, micropumps have to accomplish the fluid transport. In the latter case, conventional technology such as syringe pumps may be used.

The micropump concepts and technologies having been developed over the past 25 years are nicely reviewed in a recent article by Laser and Santiago [7]. There seem to be two most popular pumping principles which many pumps rely on: volume deflection by a diaphragm and electroosmotic flow. Corresponding pump designs are sketched in Figs. 5 and 6. Diaphragm pumps rely on volume displacement by deflection of a diaphragm forming the boundary of a pump chamber. Different types of actuators may be employed to evoke the deflection of the diaphragm, with piezoelectric disks being the most widespread. A directional fluid motion is usually induced with the help of passive valves in the inlet and outlet sections of the pump. Electroosmotic pumps rely on a completely different operation principle. In ionic liquids a charged Debye layer is often formed in the proximity of a solid surface, with the consequence that the liquid acquires a net charge. When applying an electric field a force is exerted leading to motion of the liquid along the field lines.

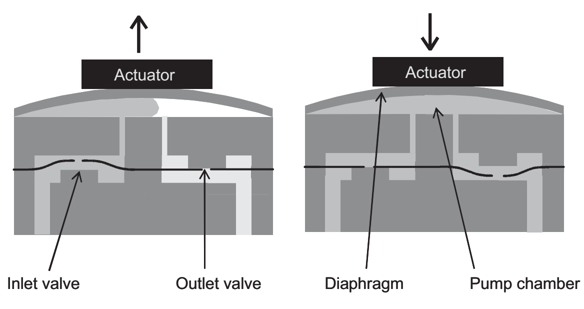

Figure 5: Design and operation principle of a diaphragm pump.

Electroosmotic pumps have the advantage that, owing to the simple design, the effort for microfabrication and microassembly is very small. Furthermore, the elctroosmotic flow profile has almost a plug-flow shape, thus minimizing the detrimental effects of sample dispersion. A further advantage lies in the steady, pulsation-free fluid transport. Disadvantages are the creation of gas bubbles due to electrolysis, the limited flow rates and the limitation to liquid pumping. In contrast to that, diaphragm pumps do not create gas bubbles, allow for higher flow rates and are often suited for both liquids and gases. Their disadvantages lie in the large efforts for microfabrication and -assembly, in sample dispersion due to Poiseuille flow, and in flow-rate pulsations due to the periodic diaphragm displacement.

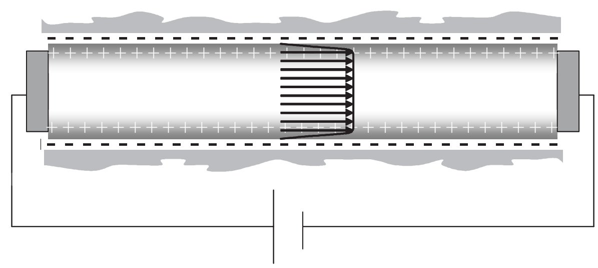

Figure 6: Sketch of an electroosmotic pump and the induced flow pattern.

The monolithic design concept discussed in section 2 allows for different mechanisms of fluid transport. One of the operations achievable with the array of fluidic actuators is usually fluid transport, such that, truly in terms of a monolithic system, no separate pumping unit is needed. Instead, the motion of droplets is induced by collective action of the actuators, utilizing effects as electrowetting or acoustic streaming.

In the case of modular microfluidic systems, the fluids may be transported by diaphragm or electroosmotic pumps, but, owing to the disadvantages discussed above, the search for alternative solutions continues. In that context, pumps based on ferrofluids have recently attracted some attention [8,9], since their design is quite simple and fluid motion is initiated by an external magnetic field without the need of physically connecting the microfluidic device to an external actuator.

5 MODELING AND SIMULATION

In the development of microelectronic circuits simulation methods play a key role for ensuring that a proposed system design meets the performance requirements. Compared to that, modeling and simulation of microfluidic systems is at its infancy. The design methodology for microelectronics heavily relies on dependable component models which are largely missing in microfluidics, partly because the Lab-on-a-Chip and µTAS developers have not agreed on the generic components of microfluidic circuits. As soon as such component models are available, system simulation may proceed in a manner very similar to microelectronics, as exemplified in some recent articles [10,11].

In order to study the performance of microfluidic structures and components in a systematic way, CFD simulations may be employed. In that context, the question has often been addressed whether or not the usual continuum descriptions may be used for that purpose. Most researchers would agree that, apart from a few special cases, the macroscopic transport equations provide a sound basis for studying fluid flow in microstructures characteristic for Lab Chips and μTAS. As a consequence, deriving components models from CFD simulations appears as a rewarding strategy for single-phase flow. While from single-phase simulations reliable information for component performance can be expected, the situation is more involved for two-phase flow. Two-phase flow in microstructures almost inevitably includes moving contact lines, and the complex contact line dynamics involving such effects as dynamic contact angles and contact angle hysteresis largely determines the motion of small droplets or bubbles.

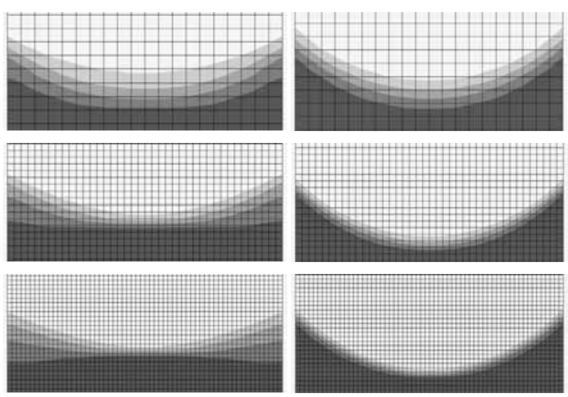

Figure 7: Shape of a moving capillary meniscus obtained in CFD simulations on different computational grids. Left column: Standard CFD results. Right column: Results of an empirical CFD model with prescribed static contact angle.

The problem with microscopic two-phase flows is that, owing to the contact line dynamics, CFD models do usually not allow a reliable prediction of the flow. Thus, one gap to be closed on the way to reliable component models for microfluidics is the formulation of CFD-based approaches for flows with moving contact lines. A step along that route is, e.g., the development of a CFD model for contact-line dynamics as reported in [11]. Using an experimental correlation for the dynamic contact angle reasonable results for contact-line dynamics may be obtained on comparatively coarse computational grids, in sharp contrast to a straightforward CFD calculation which usually requires a large grid resolution. Fig. 7 compares standard CFD results exhibiting a pronounced grid dependence to results of such an empirical model obtained for a prescribed static contact angle. Effective models implemented into a CFD framework allow to study moving-contact line problems in realistic 3D geometries with acceptable computational effort and thus help to establish component models for two-phase microflows.

6 CONCLUSIONS

In this review the design paradigms and methodologies for microfluidic systems were briefly discussed by illuminating the aspects of distribution of functionalities, flow patterns, fluid transport, and modeling and simulation. Clearly, due to space limitations other important aspects such as mixing had to be omitted. While there are some preferred solutions for specific problems, the microfluidics engineers do not yet seem to have agreed on anything as generic design concepts comparable to those existing in microelectronic circuit design. However, in the last years a trend towards two-phase micro flows has emerged, and the first monolithic “fluid processors” have appeared. If this trend consolidates, one of the gaps to be closed lies in the development of CFD tools for flows with moving contact lines which yield realistic results for realistic geometries.

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