Modelling and Optimization of Medical Test Strips Made From Plastics

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ABSTRACT

In cooperation with the industrial partner STEAG microParts GmbH and the Karlsruhe Research Center, a behavioural model for the microsystem ‚Medical Test Strips' has been created and optimized by the authors in order to decrease cost and effort in the design process. As there is no complete theory for the underlying system yet, with capillar interaction between up to three different materials, the flow of liquids in such an application cannot be described analytically. The system contains microchannels, structured with small columns or lamellae to increase the fluidic resistance. Quantities of interest are the volume flow and the filling time of the channel, related to the system geometry and material properties. They determine the retention period of the liquid and therefore the time for chemical reactions as essential parameters concerning functionality.

Keywords: Microfluidics, Modelling, Optimization, Medical Test Strips

1 INTRODUCTION

Today, the design process for microelectronic circuits and microchip layouts can be carried out under highly standardized conditions and well-defined working environments. Engineers have access to extensive model libraries, allowing to simulate complex circuit designs before manufacturing. The underlying model descriptions for electrical components take into account functional behavior as well as technological parameters. Normally, the obtained simulation results yield reliable predictions concerning system performance and can be verified by measurement.

However, there is no equivalent in microsystem design. Microsystems often combine quantities from different physical domains as they allow electrical, mechanical, fluidical or thermal interaction. Developing simulation models for such hybrid microsystems usually results in custom solutions, which are highly specific and provide little reusability.

Optimal designs are still found by heuristic approaches as trial and error methods, including many redesign cycles. This can lead to disadvantages concerning economic parameters like manpower, development expenses and time to market.

To overcome the situation, great efforts are being made to create modular model libraries for microsystems, as well as to implement modelling, simulation and model-based optimization in the design process [1].

This paper presents a modelling approach leading to model-based optimization of the microsystem Medical Test Strips. An optimal set of geometry parameters has been found and handed to the manufacturer.

2 MEDICAL TEST STRIPS

Medical Test Strips made from plastics are an innovative approach towards cheap and therefore seminal one-way diagnostic systems and can be considered as a step towards the long discussed ‚lab on a chip'. Main field of application is the analysis of body liquids as blood and urine in regard to the diagnose of antibodies for certain diseases or the examination of other particular characteristics.

After the liquid under investigation has been filled into a reservoir, capillar forces lead to a spread through the microchannel, which is structured with small columns of defined dimensions to increase the fluidic resistance (fig. 1).

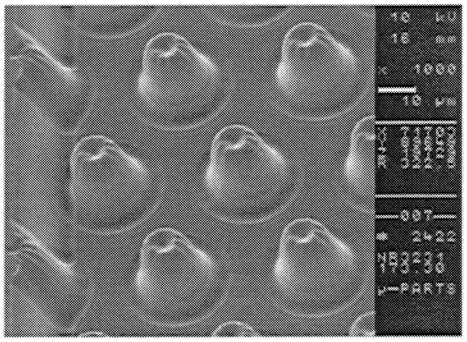


Figure 1: Structured microchannel

To obtain defined volume flow and therefore defined time for chemical reactions, the geometry parameters structure pitch and structure height have to be adjusted. Several physical parameters have to be taken into consideration as the contact angle between up to three different materials, density and viscosity of the involved liquids, as well as the etching angle of the fabrication process [3]. Channels with different geometric dimensions have been instantiated and measured to get the necessary data base for the generation of a behavioural model.

3 MODELLING

The filling of a channel can be separated into three partial flows as in figure 2, taking place in three different areas with dynamic boundaries [4].

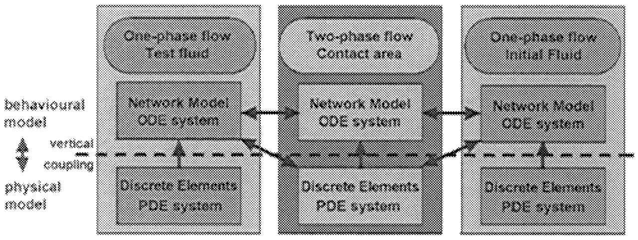


Figure 2: Modelling concept

The flow is considered as a two-phase flow in the contact area between the incoming liquid and the displaced liquid or air and as a single-phase flow in front and behind.

The interaction between fluid, air and channel material within micrometer dimensions cannot be described analytically. Surface and volume effects lead to different consequences with shrinking dimensions, as holds true for capillar forces. For each flow area of the channel, as well as for different geometric dimensions, fluidic finite volume method simulations (FVM) have been carried out, yielding information for investigated partial structures by solving partial differential equations. Due to calculation time and effort, only small parts of a channel can be simulated, so the channel has to be divided into recurrent fluidic cells (fig. 3).

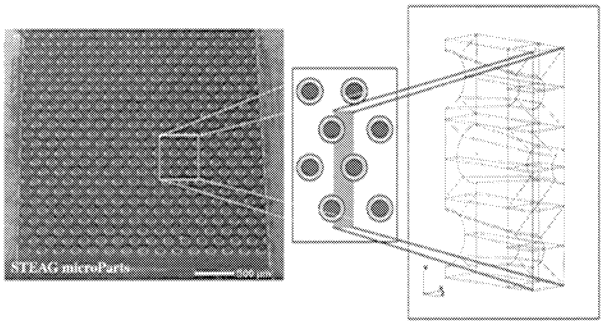


Figure 3: Partitioning of a channel

The corresponding cells have been selected in a way that the partial results can be used for extrapolation concerning complete channels, due to system symmetry.

3.1 Fluidic Simulations

Single-phase flow simulations can provide the coherence between the pressure over a fluidic cell and the resulting volume flow, resembling voltage and current as across and through variables for electric components. A corresponding network approach is applied for modelling. Figure 4 shows a steady state simulation result, yielding pressure and volume flow in a fluidic cell as described above.

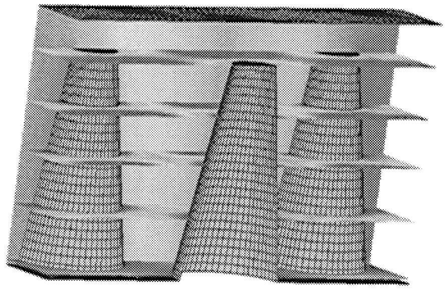


Figure 4: One-phase flow simulation

The columns are represented by the meshing grid, the pressure drops from the left to the right end of the cell, as can be seen in the background, and the horizontal planes are coloured according to the volume flow. From this, the cell resistance can be obtained and the total channel resistance as well as the channel flow can be applied to a behavioral model.

To get information about the two-phase flow, the filling of a cell has been simulated. Simulation output is shown in figure 5.

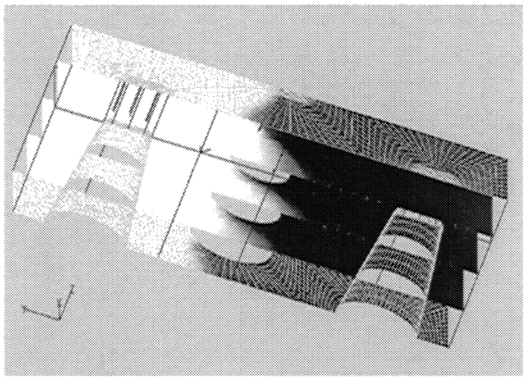


Figure 5: Two-phase flow simulation

The white air is displaced by the black liquid only by capillar forces, which can be extracted from the results. Liquid movement is initiated by the channel walls, but results show that the capillar flow is enforced by the structure elements in the channel.

3.2 Behavioral Model

As FVM simulations cannot provide results for a complete channel, a C-code behavioural model has been created on a higher abstraction level. The obtained FVM data has been transferred into analytical dependencies by applying approximation and model generation tools developed by the authors [2]. The characteristic functions with approximated adjustable parameters are used to evaluate operating points for the fluidic resistance. Figure 6 shows the approximation of the volume flow for different values of the channel height.

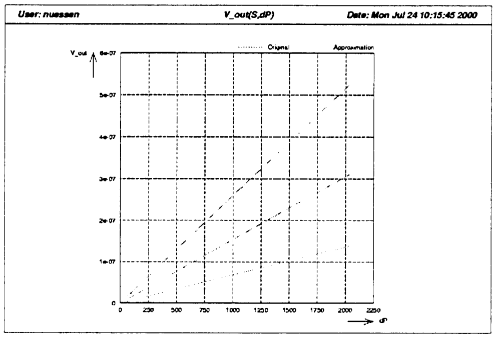
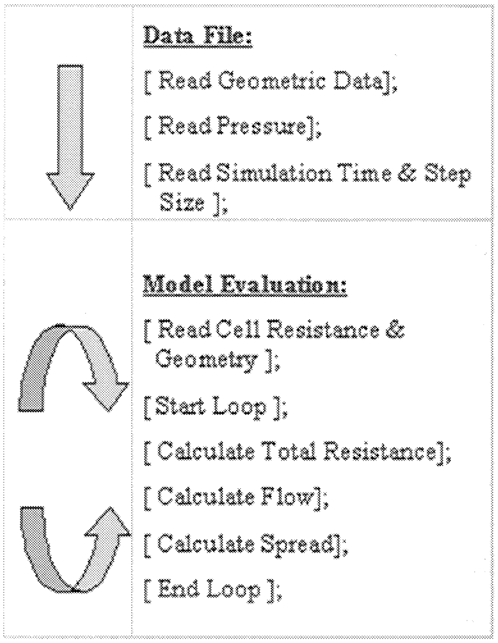


Figure 6: Approximation of simulation results

3.3 Transient Simulation

The model structure varies dynamically during transient simulation. While the channel is filled with liquid, the flow resistance of the instantiated fluidic cells, and therefore the total resistance over the channel, changes.



Data File:

[Read Geometric Data];

[Read Pressure];

[Read Simulation Time & Step Size];

Model Evaluation:

[Read Cell Resistance & Geometry];

[Start Loop];

[Calculate Total Resistance];

[Calculate Flow];

[Calculate Spread];

[End Loop];

Figure 7: Transient simulation procedure

Figure 7 shows the procedure for transient simulation. The flow, given in m^3/s, defines the spread in flow direction, measured in m/s, according to the channel geometry. From this, the position of the contact area can be calculated as simulation output.

In Figure 8 the typical meniscus in the contact line can be seen that appears during the filling of a channel.

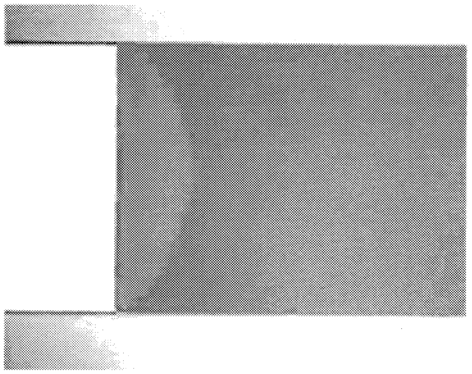


Figure 8: Meniscus-shaped contact area

This effect is implemented in the behavioural model by matrix partitioning of the channel. The meniscus shape can be defined by a bending function and by its transient occurrence, as a function of time and location. This information is taken into consideration when calculating the liquid spread. Each cell can be adressed by matrix indices as shown in figure 9.

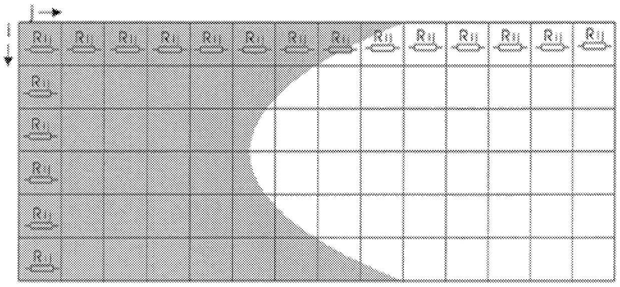


Figure 9: Modelling the meniscus shape of the contact area

The channel resistance now has to be calculated by

$$(R_{channel})^{-1} = \sum_{i=1}^{nq} \sum_{j=1}^{nl} (R_{ij})^{-1} ,$$

with *nq:* number of cells in a row, *nl:* number of cells in a line of the the channel matrix, *Rij:* fluidic cell resistance. The meniscus can be traced back to capillar forces. The capillar effect is modelled using wandering pressure sources within the channel as indicated in figure 10.

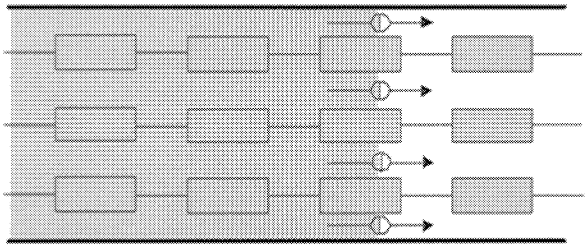


Figure 10: Modelling of capillar forces

The spread is based only on capillar forces, which refers to a realistic application without external pressure.

4 OPTIMIZATION

Main goal of investigation has been to obtain an optimal set of the goemetry parameters structure height and structure pitch, yielding a predefined filling time.

Modelling work has been focusing on creating a simulation model for optimization. This begins with the reduction of calculation time, suitable for optimization runs and ends with a self-developed time step control to save further simulation effort. The flow has a maximum at the beginning of each simulation and is slowing down afterwards, using a time step that avoids overshooting and therefore omitting fluidic cells, leads to unrealistic simulation time. Limitation of spread according to the boundaries between fluidic cells, best described as 'spread step control', appears to be most effective. Figure 11 shows the benefit of three orders of magnitude in model evaluations.

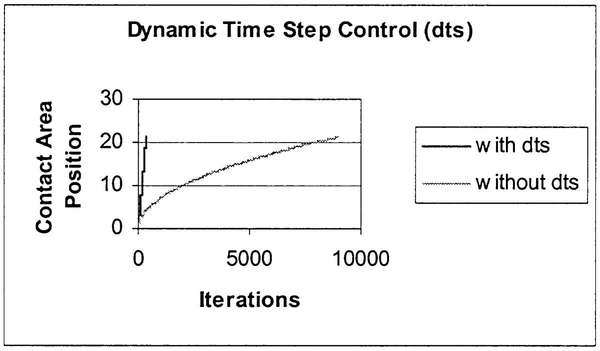


Figure 11: Time step control benefit

4-dimensional relations between pressure, flow, height and pitch, derived from FVM simulations, have been transferred into analytical equations to maintain a continuous numerical optimization space. A target function has been chosen for pressure and flow and its approximated parameters have been correlated with variations of the geometric parameters.

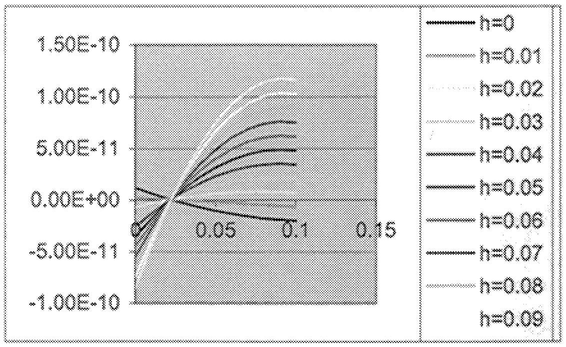


Figure 12: Approximation of a function parameter

Figure 12 displays an approximation result for a numeric parameter of the target function. It can be approximated again by a three dimensional expression that can be put back into the target function.

As pitch and height of the microstructures have similar effects on the filling time, the result has to be an optimal functional relation as shown in figure 13. The results have been obtained using one dimensional optimization methods.

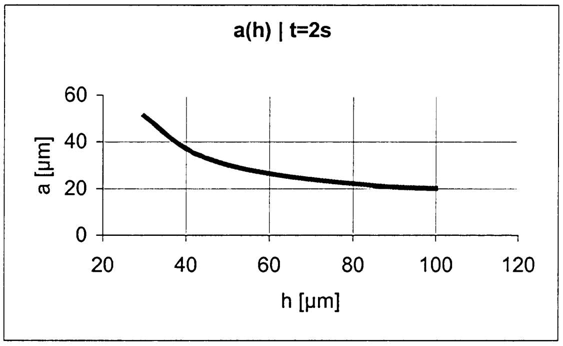


Figure 13: Optimization result

5 CONCLUSIONS

A behavioral model has been created for the microsystem Medical Test Strips and model-based optimization has been performed. An optimal relation between geometry parameters can be found for any predefined filling time of the structured microchannel.

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REFERENCES

[1] O. Nüssen et al.: An application specific design methodology for microsystems, DTIP2001, Cannes, Proceedings pp. 175-186

[2] M. Anton et al.: Computer aided modeling of static and dynamic transfer characteristics, Technical Proceedings of MSM98, April 6-8, 1998, Santa Clara, California

[3] C. Schön, I. Ballhorn: Betrachtung des Flüssigkeitsverhaltens in medizinischen Teststreifen aus Kunststoff, Statusseminar OMID, Okt. 2001, Bremen, Proceedings

[4] S. Halstenberg, A. Quinte, H. Eggert, C. Schön, R. Peters: Einsatz numerischer Verfahren zur Modellbildung und Simulation von kapillarisch getriebenen Fluiden in Mikrostrukturen. 4. Statuskolloquium des Programms Mikrosystemtechnik, 30./31. März 2000, Forschungszentrum Karlsruhe, FZKA 6423, S. 143-148