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SYNTHESIS REPORT

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MICROPUMP BASED ON LIGA AND SILICON TECHNOLOGY (MICROBLAST)

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Title

Micropump based on LIGA and silicon technology

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1 ABSTRACT

The main objectives of the project have been achieved. Following the defined tasks, these are modelling, simulation and design of (parts) of micropumps, characterisation of materials properties, fabrication of LIGA based micropumps, characterisation of micropumps and the comparison of silicon micromachining and LIGA fabrication technology.

The developed membrane micropump, featuring an unique and innovative design, exhibits outstanding technical performance in combination with a really easy and uncomplicated handling. Those pumps, with outer dimensions of 12 x 12 x 3 mm are the first micropumps working equally well with gases and liquids, exhibiting a really reliable self filling behaviour with liquids. The maximum flow rates are 250 µl/min for water and 2 ml/min for air. Using water the pump can build up pressures of more than 1200 hPa, using air the maximum back pressure is still around 500 hPa. Self filling of the micropumps is enabled by their ability to create a vacuum of 350 hPa.

Miniaturised gear pumps have been developed, which are particularly suited for use with high viscosity liquids like e.g. oil. The micro gear pumps with outer dimensions of 10 mm x 10 mm x 30 mm are driven by small electromagnetic motors. The micro gear wheels with diameters of 596 µm and 1192 µm have been realised by LIGA technology. Using oil as pumping medium the pumps achieve back pressure of far more than 1200 hPa and flow rates of up to 1 ml/min. The self filling pumps tolerate air bubbles and particles contained in the working medium. The very small volumes displaced of just 82 nl respectively 213 nl per revolution offer the possibility of very precise dosing of viscous fluids such as oil.

The design work has been supported by extended simulations using commercial (and well-known) FEM packages and the system modelling tool CAMAS/20-Sim. Substantial understanding of the fluidic and mechanical behaviour of micropumps and their components, in particular membrane valves, has been gained. New additions to the existing commercial software is a coupled fluid and mechanics solver FAME, which has been developed within the MicroBLAST project.

An optimisation technique for mechanical parameter extraction has been developed and is successfully used with silicon nitride and titanium membranes. An auto-focus optical set-up to measure membrane deflections has been fabricated which, combined with an optimisation program for mechanical parameter extraction enables the parameter extraction.

Apart from the (further) development of LIGA based fabrication technology dedicated to micropumps special assembly techniques for microfluidic systems, including laser welding, integrated tubing and self-alignment structures, have been developed. In addition, an alternative fabrication technology for high aspect ratio structures, DEEMO (Dry Etching Electroplating and Moulding), has been evaluated to be feasible for applications for less extreme requirements (aspect ratio, wall smoothness).

A flexible characterisation and test set-up for microfluidic components and systems has been developed and used to get insight in the possibilities of (LIGA-fabricated) micropumps for future applications. The characterisation set-up consists of a fluid part, sensors (flow and pressure), driving and sensor interface electronics and is controlled by a LabVIEW application VI set.

The set up is flexible and allows the automatic execution of a number of measurement protocols under software control. Further, the characterisation set-up has been implemented with a priming system based on carbon dioxide which eases characterisation and test in general and of complete microfluidic systems (e.g. micro analysis systems μTas) specifically.

In the framework of an analysis and comparison of the LIGA-technology and silicon micromachining, an inventory study resulted in a table on the pro's and con's of LIGA, LIGA-like (DEEMO) and advanced precision mechanics techniques. Compared to silicon based pumps the developed LIGA pump shows special features such as low fabrication costs at high volume production, robustness and (potential) material properties as chemical resistivity and biocompatibility. It can be concluded that each technology has to be considered in a device development. Depending on the specific aspects regarding the device the appropriate (combination of) techniques has to be chosen.

2 INTRODUCTION

Miniaturisation of devices has become one of the most important R&D areas, which is e.g. illustrated by the fact that the EC gives and has given extra attention to microsystems technology the last years (in the framework of ESPRIT and Brite-EuRAM R&D-projects, EUROPRACTICE Basic Services). The potentials of microdevices and microsystems are widespread, ranging from microsensors like pressure sensors and microactuators up to microsystems like micro total analysis systems (µTas).
These microdevices will play an important role in automotive, medical devices, process control and environmental monitoring.

The overall objective of the project has been the development of an innovative micropump for liquids by combining the possibilities for cost effective microstructuring of a large variety of materials by the LIGA-process with the know-how accumulated during many years in development of silicon micropumps. In the mean time LIGA based micropumps for gases are being developed [1,2].

Applications for (liquid) micropumps range from medical technical technology (dosing of drugs, infusion systems), chemical industry (micro reaction systems, miniature chemical analysis systems for on-line process and quality control) to environmental technology (emission measurement systems, hand-held equipment). Due to the large volume of business regarding products in the above mentioned application areas the economic potential of micropumps is estimated to be very high.

A strategic objective of MicroBLAST has been the enhancement of the current leading position of Europe in LIGA and related microfabrication technologies by applying LIGA in a micro product with high commercial prospects, such as micropumps. The project has been striven to achieve this objective by combining the strength of two leading research centres with complementary expertise in conjunction with a development company with experience in technology transfer in microsystems technology and a large number of potential users as endorsers.

3 TECHNICAL DESCRIPTION

The technical work comprised four main tasks described below.

- Modelling and simulation studies in order to generate designs for a LIGA based micropump

The specific objective has been the creation of a modelling and simulation environment for micropumps. The normal procedure would be starting with modelling and simulation resulting in the technological boundary conditions, followed by the fabrication of the working model. In this project however, the modelling and simulation task and the fabrication task started simultaneously and interacted continuously during the project. The work included FEM based modelling and simulation on forces, pressures and material stresses, system modelling and the development of FAME, a coupled fluid and mechanics solver.

Different driving mechanisms have been studied, like the deformation of bimorphic systems, the application of the well known piezoeffect and electromagnetic and thermal driving systems. Further, the micromoulding process has been simulated in order to optimise mould insert design.

- Characterisation of material properties like thermal, mechanical, electrical and chemical properties

These properties can be divided up in two classes: “standard” properties which are valid in the “macro” as well in the “micro” environment and generally available in literature, and specific “micro” properties which have to determined by dedicated experiments, modelling and characterisation. In the project both literature study and experiments have been executed.

- Development of the fabrication process and the working models of the micropump

For the fabrication process, different techniques has been looked upon. Main emphasis has been given to a cost effective replication process. Therefore, hot embossing and micromoulding have been studied and the feasibility of an alternative to LIGA mould fabrication, DEEMO (Dry Etching Electroplating and MOulding), has been investigated. The abandoning of monolithic fabrication and the using of a hybrid product structure has been offering the opportunity for combining the advantages of different materials and fabrication processes.

- Evaluation of the performance of the micropump

Next to a measurement system for direct feedback during the development of working models, a flexible microfluidic characterisation set-up, including different driving electronics as well as (standardised) characterisation protocols has been developed. The set-up is controlled by LabVIEW, making it possible to execute a series of measurement protocols automatically.

4 DESCRIPTION OF RESULTS

The most important result of the project has been the development of a LIGA based micropump with excellent specifications, such as the self filling property and a high backpressure in the order of 1000 hPa.
In the sections below the main results are described and some details are given.

4.1 LIGA based micropumps

- Membrane pumps

In the course of the project several generations of membrane micropumps fabricated from polymer materials by LIGA and related technologies have been successfully developed [3,4]. The last generation of membrane micropumps, featuring an unique and innovative design, exhibits outstanding technical performance in combination with a really easy and uncomplicated handling. Those polymer pumps with outer dimensions of 12 x 12 x 3 mm are very robust and are the first micropumps working equally well with gases and liquids, exhibiting a really reliable self filling behaviour with liquids. The performance of those piezo driven membrane pumps can be summarised by the following data. The maximum flow rates are 250 µl/min for water and 2 ml/min for air. Using water the pump can build up pressures of more than 1200 hPa, using air the maximum back pressure is still around 500 hPa. Self filling of the micropumps is enabled by their ability to create a vacuum of 350 hPa.
Figure 4.1 shows a typical flow pressure characteristic of the realized micropumps.

Figure 4.1 Flow-pressure characteristic LIGA pump (design 4).

In figure 4.2 a photograph is shown of the working model of the pump. The basic principle is adopted from the piezoelectric membrane pump of Van Lintel [5]. However, in the case of the LIGA micropump the detailed design is adapted, the parts are fabricated on the basis of the LIGA technique and are of polymer material. The assembly of the parts is done with laser welding, providing the necessary leak tight sealing and which does not affect the structural properties of the polymer parts.

Figure 4.2 Working model of membrane micropump

The membrane micropumps developed thus feature a performance far superior to any micropump previously reported in the literature. In particular the reliable self filling capability opens up a vast number of new applications for micropump. In addition the new micropump design allows for a very cost effective mass production. For large volume production fabrication costs of 1 DM or lower seem feasible.
In figure 4.3 a typical flowrate vs. pressure characteristic is given.

Figure 4.3 Flowrate vs. pressure characteristic of membrane pump

- Gear pumps

In addition to the membrane micropumps miniaturised gear pumps have been developed, which are particularly suited for use with high viscosity liquids like e.g. oil [6]. The micro gear pumps with outer dimensions of 10 mm x 10 mm x 30 mm are driven by small electromagnetic motors. The micro gear wheels with diameters of 596 μm and 1192 μm have been realised by LIGA technology. Using oil as pumping medium the pumps achieve back pressure of far more than 1200 hPa and flow rates of up to 1 ml/min. The self filling pumps tolerate air bubbles and particles contained in the working medium. The very small volumes displaced of just 82 nl respectively 213 nl per revolution offer the possibility of very precise dosing of viscous fluids such as oil. In figure 4.4 a SEM view is shown of the micro gear pump.

Figure 4.4 SEM view of micro gear pump (gear wheels 596 μm).

4.2 Modelling, simulation and design

The activities can roughly be divided up in a task aimed on the development of a modelling and simulation tool regarding a micropump as a complete system and a task more directly aimed on the LIGA micropump design including (FEM) modelling of certain subsystems such as valves (see below) and actuators, and the moulding fabrication process [7].

The latest modelling tools have been used to optimise the micropump design. The design work has been supported by extended simulations using commercial (and well-known) FEM packages (ANSYS-FLOTRAN, COSMOS/M-FlowSTAR) and the system modelling tool CAMAS/20-Sim. Substantial understanding of the fluidic and mechanical behaviour of micropumps and their components, in particular membrane valves, has been gained. Additions to the existing commercial software are FIDAP and FAME. FIDAP is a commercial Computational Fluid Dynamics program and FAME is a coupled fluid and mechanics solver, which has been developed within the MicroBLAST project.

- Coupled solver FAME

FAME is an acronym for Fluid and MEchanics. This program is developed in close co-operation with the Micro-system Technology Laboratory at the Massachusetts Institute of Technology in the USA. The FAME solver has a similar structure as existing coupled solvers (other physical domains). The nature of micromechanics again caused us to address the basic physics of the devices. As opposed to macro mechanics there is a strong interaction between physical domains. Within micro-pumps conventional models of fluid flow through valves breaks down because the flow cannot force its pressure and velocities onto the structural parts (membranes) without being influenced by the membrane action itself.
This interaction can be modelled in two ways. Firstly, the mechanical and fluid behaviour can be incorporated into one differential equation. This equation can then be solved with finite elements, which means that a completely new finite element code has to be written for this coupled effect. A second way of dealing with the problem is studying the interaction between mechanical and fluidic behaviour. As is the case in other physical domain coupling, fluidics and mechanics are coupled through the physical boundary of the structure. This means that existing finite element packages can be used for each separate domain. Converting information from one domain to the other and controlling the calculations is the task of the coupled solver. The latter technique has been used in FAME.

The first version of FAME has been written half-way the MicroBLAST project. It consisted of the fluid finite element solver FIDAP (commercially available under educational licence) and a home code finite difference mechanical solver. This first version of the FAME program has been restricted in its applications since it has been only possible to use linear deflection theory which has been shown to be insufficient. Two new versions of FAME now implement the commercial structural finite element program COSMOS/M for the mechanical solver, including the non-linear mechanical solution routines, instead of the home code.

The capabilities of both solvers are shown in the following table.

	Description	**FAME_flex**	**FAME_solid**
1	Maximum no. of elements	10000	10000
2	Maximum no. of nodes	10000	10000
3	Maximum no. of iterations	50	50
4	Fluid element type	4-node Quad/Triang	4-node Quad/Triang
5	Mechanics element type	2-node 1D-Beam	plane 2D
6	Dimension	2D	2D
7	Relative mesh deformation	20% - 500%	20% - 500%

The first three limitations are determined by the hardware which is being used for the simulations. Both the HP and SUN workstations used during the calculations are low end workstations of which RAM memory, disc space and chip capabilities are limited. FIDAP is only limited by its processor resources while COSMOS/M also has limitations on all its DOF's (degree of freedom). However, the maximum number of iterations has not been the limiting factor regarding simulation failure.

Both 1- and 2-dimensional structural elements, and 2-dimensional fluid elements are allowed. This first version of FAME has been written for 2-dimensional problems for the finite elements listed above. The coupled problems which can be tackled are the cases in which the flowing fluids produce a pressure on the flexible parts of the mechanical structure. The mechanical parts do not have internal elements but consist of 1-dimensional flexible wall elements. These flexible elements can be loaded by pressures from both sides. Some simulation effects which can occur are sketched in the figure 4.5.

Figure 4.5 Simulation effects with FAME-flex.

The top figure shows a normal steady flow under a flexible membrane where the membrane deflects inward either under the influence of drag or a constant outside pressure.
The middle figure shows the filling of a beaker which expands under the fluid mass.
The lower figure shows a typical situation where this solver in no longer able to find a solution: a solid structure is modelled as a flexible wall, the fluid pressure from both sides causes the walls to deform through the other wall. The second coupled solver is named FAME_solid after the structural elements which have been implemented, making this kind of simulations possible.

The new coupled finite element program FAME has been tested on two valves. The valves have both been fabricated and measured in other projects outside MicroBLAST: a project at MESA and a project from an endorser. The results have been made available for the MicroBLAST project in order to test the numerical program FAME. The two valves have been published in references [8,9, 10]. The FAME simulations have been published in [11] and [12].

- FEM simulations on membrane valves with ANSYS-FLOTRAN

The pump designs described have been based on additional modelling work in conjunction with the simulation of the valve behaviour [13]. Good understanding of the micro membrane valves has been achieved by using coupled FEM calculations of the valve behaviour (software ANSYS / FLOTRAN).
The principal strategy employed is the following. An initial pressure distribution forms the basis for the calculation of the corresponding deflection of the valve membrane, which itself is the basis for a calculation of the established flow pattern. The resulting pressure distribution is again fed into the membrane deflection simulation procedure. The whole cycle is repeated until convergence has been achieved and a self consistent solution has been found.
The resulting flow rate vs. pressure characteristic for a 1 mm membrane valve compares very well with experimental data as shown in figure 4.6.

Figure 4.6 Simulated flow rate vs. pressure characteristic of 1 mm membrane valves in comparison to experimental data.

In order to further optimise the valve design with respect to a reduced fluidic resistance good knowledge of the pressure distribution inside the valve and the corresponding fluidic losses is of considerable importance. According the simulations for low pressure drops, i.e. low flow rates, the major part of the pressure drops occurs in the narrow "slit" underneath the membrane. However, for large pressure drops, i.e. high flow rates, by far the largest pressure drops can be observed in the vicinity of the valve opening, i.e. in the outlet of the valve. Thus for large pressure drops the valve opening of the membrane acts a diaphragm and dominates the fluidic resistance of the valve.

Other types of miniaturised valves, such as micro ball valves and valves employing diffuser / nozzle structures, have been studied theoretically and experimentally as alternatives to the membrane valves. However, the results did not lead to clear cut advantages for the alternative valves.

4.3 Materials characterisation

From literature a thermal and electrical property as well as a material bio-compatibility list has been composed.
Macro models have been created for extraction of material data from measurement on modelled structures. Therefore an auto-focus optical set-up has been developed to measure membrane deflections. The macro models are implemented in a software code. This program starts with an estimate of material data from literature, e.g. the Modulus of Elasticity, Poisson's ratio or pre-stress of a membrane. Than deflection measurements are given to the program. It than searches for a best fit between the model and the measurements while adjusting the mechanical parameters. The output of the program gives the material properties of the membrane.
Verification runs have been performed on structures of silicon nitride, titanium and polycarbonate (PC).
Important is to note that fabrication processes, such as moulding and assembly used in LIGA, may change the material properties of polymers considerably as is confirmed by experiments in the project. By proper moulding and assembly negative effects with respect to the properties of the devices can be minimised.

4.4 Fabrication technology

Apart from the development of LIGA based fabrication technology dedicated to micropumps special assembly techniques for microfluidic systems including laser welding, integrated tubing and self-alignment structures have been successfully developed in the course of the project.
Namely, the laser welding technique for the leak tight and pressure resistant connection of layered polymer microfluidic systems can be applied to a large class of other microsystems, including more complex integrated micro reaction systems.
In addition, with respect to the fabrication technologies an alternative fabrication technology for high aspect ratio structures, DEEMO (Dry Etching Electroplating and Moulding), has been evaluated to be feasible for applications for less extreme requirements (aspect ratio, wall smoothness).

- Laser welding

A new laser welding technique has been developed providing a strong and leak tight connection of the polymer layers. It facilitates fast and accurate bonding along defined tracks, which is of particular importance for devices featuring moving structures. The principle of the laser welding technique is rather simple. An optically transparent and a non-transparent thermoplastic layer are fixed on top of each other. Passing through the transparent layer, the infrared light of a Nd:YAG laser is focused on the interface between both layers. Due to the different absorption of the materials the infrared light is mainly absorbed at the surface of the non-transparent layer, leading to local melting and subsequent welding. Cuts normal to a laser welded track show no interface between the two layers. A direct contact of the two layers is not principally required, since gaps of more than 50µm have been successfully closed by foaming of the polymers. Welding tracks of less than 0.5 mm width have been achieved. Typical welding speeds amount to 5 mm/s.

The laser welding technique can be extended to stacks of more than three polymer layers by coating the layer surfaces with a thin light absorbing film after preceding laser welding steps. First steps towards mass production have been reached by using batch processing of multiple micropumps in one positioning step. The clamping of the pump parts during the welding process largely influences the quality of the connection with respect to wedge errors. A new clamping system using a vacuum chuck has been constructed and delivers very reproducible welding seams.

- DEEMO

The LIGA technology enables the fabrication of micro-mould inserts with very high aspect ratio's and results in extremely precise structured moulds. An alternative method, DEEMO (Dry Etching Electroplating and MOulding), based upon the innovations of the MESA Research Institute in the field of dry etching has been investigated on its feasibility for less extreme properties requiring applications. Like LIGA, DEEMO enables the fabrication of micro mould inserts, in the case of DEEMO of silicon, for subsequent electroplating, resulting in a metal mould insert, and the possibility of embossing and moulding, while the processing/tooling costs are much lower. The feasibility of DEEMO has been investigated and demonstrated in the project. Subsequently, an EC project has been applied for and accepted for funding, in which DEEMO is being further developed towards a technology suitable for production.

4.5 LabVIEW controlled characterisation set-up for microfluidic components and systems

The specific objective has been to design and realise a characterisation set-up with which measurements can be performed on the realised working models in a well defined and therefore reproducible way. A good repeatability of measurement results has a higher priority than accuracy. Therefor the overall measurement fault has been set on $\leq$5%. During the development of the system the functionality has been expanded e.g. with a priming system based on carbon dioxide and an accurate pump (BRAUN PERFUSER) in order to make the set-up suitable for use for all kinds of microfluidic components including micropumps, valves and flow sensors and, last but not least, complete microfluidic systems (micro analysis systems). In order to develop a flexible and optimised set-up not only LIGA-fabricated micropumps, but also other fluidic components such as other types of (silicon) pumps and flow sensors have been characterised and tested [14, 15].
All relevant documentation to be able to use and service the characterisation set-up, including a test protocol description, have been made along with the realisation of the system.
A number of characterisation and test protocols have been defined and implemented in LabVIEW.

- Trumpet-curve (long-term flow test)

The so-called trumpet-curve protocol has been developed in accordance with the IEC-62D standard that is used for testing/characterising of medical infusion pumps. In this way the performance of the devices under test can easily be compared with existing pump devices. An advantage of using the so-called "trumpet-curves" is the ability to evaluate a pump for its use in a control loop.

Essentially, the trumpet-curve describes the stability of the output flow as a function of time under constant conditions, i.e. driving settings (minimum, intermediate and maximum flow) and pressure load (positive, negative or no back pressure). Ideally, for each condition a trumpet-curve is realized. In practice this would mean 9 * 2 hours measuring, and normally this full range

of measurements is only done in special cases.
To derive the trumpet-curve a registration of the flow over a certain time interval under a combination of the above mentioned conditions is acquired. In medical applications a length of registration of 1 hour is used (after 1 hour stabilizing time), but this length is not essential for the method. The overall average of the flow over the measuring interval is calculated, and eventually the average error in relation with the set flow is derived.
Using a moving time interval of length x, the minimum and maximum value of the average flow over x is calculated. By repeating this step with a range of values for x, the graph of minimum and maximum values as a function of x form the trumpet-curve (see for an example figure 4.7 below). At x = registration length, the minimum and maximum value will be equal to the overall average of the flow. With decreasing x, in most cases min and max values will increase in absolute value.

Figure 4.7 Trumpet curve LIGA pump (design 4).

For dosing purposes the trumpet-curve shows the ability of a pump to deliver a certain volume within a certain time interval at a certain accuracy. In medical applications this is of importance, especially when highly active medicines are involved. By adapting the trumpet-curve parameters (which are standardised for medical applications) the use of the trumpet-curve could be extended to stability calculations on feedback systems, i.e. in a pump - flow sensor combination.

4.6 Comparison of LIGA and silicon micromachining

Several surveys have been conducted in this project for the comparison of LIGA and silicon micromachining. The two fabrication techniques are quite different. Both can be presented in a list of criteria for High Aspect Ratio Manufacturing Technologies (HARMT). This list can be used as a starting point for the rough assessment on manufacturing techniques regarding a specific device or system development.

These criteria are: maximum aspect ratio, geometrical freedom in two & three dimensions, batch versus single structure processing, anisotropy, roughness, resolution and accuracy. During the running of the project it became clear that it was relevant to involve more advanced precision machining techniques which has made great progress such as UV-lithography (followed by electroplating and moulding), LIGA, laser ablation, ion milling, spark erosion and DEEMO. This resulted in an inventory table with pro's, con's and characteristics of the different techniques.

Based on the results in the project special features of the LIGA based pump are the excellent performance, self filling property, the potential low fabrication costs at high volume production and the polymer material properties, making the pump very robust and potentially chemical resistant and/or biocompatible.

5 CONCLUSIONS

In the project a LIGA based micropump has been developed with better specifications than set as objectives in the proposal. Namely, the self filling property and the high back pressure in the order of 1000 hPa are very remarkable. The results achieved in the project prove that practical application of a moulding based (plastic) micropump is possible, having the advantage of low fabrication costs at (very) high volumes. The low fabrication costs in combination with the excellent technical performance will open up new possibilities for applications of micropumps. Besides, further special features of the LIGA based (membrane) pumps compared to silicon based pumps are the choice in use of polymers with respect to chemical resistance and/or biocompatibality and the robustness of the polymer material.

An important aspect for further development is the realisation of automated assembly processes, which will largely determine the fabrication costs.

The work on modelling and simulation resulted in the development of a new coupled solver FAME. In combination with the use of existing modelling and simulation tools this FAME is a very suitable modelling tool to optimise the micropump design.

Thermal and electrical properties of commercially acquired membranes do not deviate from vendors information. The optimisation technique for mechanical parameter extraction has been successful used with silicon nitride and titanium membranes. An important conclusion is that the fabrication process, and especially moulding processes, can alter the material properties considerable. It is therefore recommended that material properties are measured on fabricated devices. These measurements can than be inserted in the material property optimisation software which gives the actual properties. Results can be used in optimising models, simulations and design.

The feasibility of DEEMO as a technology to fabricate mould inserts and embossing structures with high aspect ratio's has been demonstrated. The results in a succeeding EC project, focussed on industrialisation of the DEEMO technology, have to be awaited before it is clear whether DEEMO is applicable in production processes.
Based on the inventory on high aspect ratio techniques including advanced precision mechanics, it can be concluded that each technology has to be considered in a device development. Depending on the specific aspects regarding the device the suitable (combination of) techniques has to be chosen.

The developed microfluidic characterisation set-up is flexible and its use is simple and user-friendly. In case that it is necessary to adapt the system to new demands the system specifications can easily be changed both on hardware (addition or replacement of components) and software level (addition of new VI's or command files). In addition to pressure-flow diagrams as a performance test, the so-called trumpet-curve approach gives additional information to the characterisation of a micropump.

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