Microactuators for Powerful Pumps

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Abstract

When paraffin wax melts it exhibits a large, relatively incompressible volume expansion. This can be used in microactuators for strong and large displacements, a rare combination among actuators. Furthermore, paraffin is inexpensive, inert and environmentally friendly, as well as easily processed and actuated. Together, these properties give paraffin actuators great potential for use in both low-cost and high-performance applications.

In microfluidics, the miniaturization of various analysis systems decreases the volumes of samples and reagents needed, as well as the analysis throughput time. Using on-chip micropumps increases the efficiency of the microfluidic system, but a challenge for such pumps is the high back-pressure associated with separation, filtration or narrower channels.

The objective of this thesis is to increase the understanding of paraffin in microactuators, as well as to further explore its possibilities and limitations. The main application area has been on-chip micropumps.

For low-cost applications, actuators, pumps and dispensers have been fabricated in plastics and then evaluated. The dispenser is intended for on-chip storage and dispensing of liquids in a lab-on-a-chip that could be used in, e.g., point-of-care testing (POCT).

For high-performance applications, metallic actuators, pumps and dispensers have been accomplished. The micropump is the world’s strongest mechanical micropump in sub-cubic centimetre size, capable of pressures of above 5 MPa. Possible applications are strong microhydraulics, on-chip chromatography, or medical microdosage systems.

A limitation of paraffin is the relatively slow thermal actuation. In this thesis the thermal properties have also been turned into an advantage: Directional solidification is used to accomplish multiple stable states of the actuator displacement, withheld without any power consumption.

For the future, the high-pressure capability may be improved by new designs. Optimization of speed and power consumption can be made by further work on modelling as well as on drive and control of the heating.

Keywords: μTAS, chromatography, high pressure, lab-on-a-chip, microactuator, microdispenser, micropump, on-chip, paraffin, PCM, point-of-care

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“A complex system that works is invariably found to have evolved from a simple system that works.”

- John Gaule
List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I  A polymeric paraffin microactuator
   2008 *J. Microelectromech. Syst.* 17(5) 1172-7

II  A multi-stable miniature paraffin actuator
   Lehto M and Bodén R
   2008 *Proc. Actuator* pp 864-7

III A paraffin driven linear microactuator for high force and large displacement applications
    Bodén R, Lehto M and Schweitz J -Å
    2006 *Proc. Actuator* pp 720-3

IV  A polymeric paraffin actuated high-pressure micropump
    2006 *Sensors Actuators A* 127(1) 88-93

V   A metallic micropump for high-pressure microfluidics
    Bodén R, Hjort K, Schweitz J -Å and Simu U
    2008 *J. Micromech. Microeng.* 18(11) p 115009

VI  A paraffin-actuated, high-pressure microdispenser pump
    Bodén R, Ogden S and Hjort K
    Submitted, November 2008 *J. Micromech. Microeng.*

VII On-chip liquid storage and dispensing for lab-on-a-chip applications
    2008 *J. Micromech. Microeng.* 18(7) p 075036

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The author’s contribution to the papers

I    Major part of planning, evaluation and writing, most part of fabrication

II    Major part of planning, evaluation and writing, most part of fabrication

III   Most part of planning and writing, all experimental work

IV    Major part of planning and experimental work, most part of writing

V     Most part of planning and writing, all experimental work

VI    Major part of planning and experimental work, most part of writing

VII   Major part of planning and experimental work, most part of writing
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1 Introduction

Microsystems technology (MST) is about making systems, or parts thereof, smaller. Making them smaller can reduce cost and increase their performance by reducing response times as well as increasing portability, sensitivity and availability. It can even introduce new functionality [1]. The “muscles” in these microsystems are called microactuators. One example of a commercialized microactuator product is the Digital Micromirror Device™ (DMD) from Texas Instruments, used for controlling micromirror arrays for projection displays. Another example is micromotors for focusing the lens in compact cameras.

Microfluidics is the part of MST that deals with drive and control of fluids, i.e., gases and liquids [2]. In this field, microactuators can be used to drive pumps and valves. One example of a wide-spread microfluidic application is printer heads in inkjet printers. Exciting applications of the future include handheld laboratories for personal health diagnostics or for analyzing environmental samples out in the field.

Already, there are a lot of different microactuator types available. However, for many applications there is still a need to find new, better suited actuators or actuator materials. In many cases, the ideal actuator material has a large expansion while at the same time withholding a large pressure. This is especially important when miniaturizing actuators, in order to preserve as much of the actuator performance as possible. One example of such a material is paraffin in its phase transformation from solid to liquid. Some research has already been made on paraffin, however, not enough for paraffin to become an established and well-known alternative in Microsystems.

1.1 Aims

The objective of this thesis work is to increase the understanding of paraffin as an actuator material in miniaturized applications. The three main aims are to:

- Further evaluate paraffin as an actuator material.
- Find applications benefiting from the actuator properties of paraffin.
- Explore the limits of paraffin in microactuators.
The chosen methods for accomplishing these aims are to design, fabricate, and evaluate paraffin actuators and paraffin-actuated systems, as well as modelling the thermomechanical behaviour of paraffin.

As will be discussed further on, paraffin is an actuator material with low compressibility and large volume expansion when melted, giving it a great potential for large-stroke microactuators with high forces. However, the thermal actuation in combination with its low thermal conductivity, high specific heat capacity and large amount of latent heat puts paraffin among the slower actuator materials.

For this reason, the main hypothesis of this work is that paraffin should be particularly suitable for pumping liquids at high pressures in applications where a low flow rate is preferable. However, other interesting applications are evaluated as well, in order to get a more complete picture of paraffin actuation.
2 Background

Here follows a short background of microsystems technology (MST) and microfluidics, more information can be found in [1] and [2], respectively.

2.1 Microsystems technology

In MST, the term micro generally means that the size of a component is in the micrometer range in at least one dimension. The technology is very multidisciplinary and a single system may use biological, physical and chemical principles to solve its tasks. Another name for MST is microelectromechanical systems (MEMS).

MST has its roots in the integrated circuits (IC) technology which uses mainly silicon substrates. The silicon processing methods were adapted to create other structures than just electronic circuits on the chips; hence MST sometimes stands for microstructure technology. Nowadays, additional materials like polymers and glasses are used for microstructures and microsystems. Polymers are often used to reduce production cost for large area components and systems, as silicon processing is still relatively expensive for such production.

Examples of research areas currently of interest for MST are radio frequency and optical communication systems, as well as micro fuel cells, in applications like, e.g., laptop computers and cell phones [3].

2.2 Microfluidics

There are essentially two points of view on the meaning of micro in microfluidics: For people working in the MST field, it often relates to the size of the device. People using microfluidics only for the new effects and better performance, often chemists or biochemists, relates to it as the size of the fluid quantities in the device [2]. Interesting to remember is that a microlitre is equal to a cubic millimetre, i.e., one billion cubic micrometres.

Microfluidic structures are generally larger than other structures in MST. One reason is that the channels often have a large cross-section area since the back-pressure in a channel increases with decreasing cross-section area. Also, for optical analysis channels often need to be wide in order to increase
the visible detection area. Another reason is that the channels often need to be rather long, in order to enable diffusion processes to take place in mixing or chemical reactions, or to simply transport the fluid from one part of the system to another. Hence, the total area occupied by a channel system becomes much larger (up to several square centimetres) than for many other microstructures.

An area of microfluidics of increasing interest is lab-on-a-chip (LOC) and micro total analysis systems (μTAS) [4–7]. In this area, the objective is to miniaturize and integrate the components of a laboratory on a chip. Ideally, the whole laboratory – from sample preparation to analysis – should be integrated into one single chip. Ultimately, a true μTAS drastically decreases the analysis time as well as the required volumes of samples that may be hard to come by and of reagents that are often expensive. A portable or even handheld μTAS has great potential for the future. It could be used by, e.g., patients for health diagnostics in their own homes, an example of point-of-care testing (POCT), or by researchers for performing analysis of various samples out in the field. An example of a handheld POCT device on the market is the i-STAT® from Abbott Laboratories. From a few drops of blood, this device can analyze sodium, potassium, chloride, ionized calcium, urea, nitrogen, glucose, hematocrit, and blood gases [8].

In microfluidics, actuators are often used in various types of valves and pumps that control and drive the fluids in a system. Presently, external (off-chip) actuators are often used since on-chip actuators are not well established. However, there are several advantages of integrating microactuators into microfluidic systems. For example, external pumps often need relatively long channels or tubing to connect to the microfluidics. This increases the inactive fluid volume, i.e. dead volume, of the system, which in turn decreases response time and performance. On-chip microactuators may also allow for a decrease in size and of the energy consumption of the microfluidic system.
3 Material and characterization

Paraffin is part of everyday life. It is used in skin lotion, in candles, as chewing gum additive, and in glide wax for skis. It is also used as an actuator material in thermostats in various applications, e.g., in automobiles. However, there are currently no established paraffin microactuators on the market.

3.1 Paraffin properties

Paraffin consists of different compositions of straight hydrocarbon chains (n-alkanes, C\textsubscript{2n}H\textsubscript{2n+2}) with different lengths. Depending on the composition, the melting point for paraffin wax can be up to 150°C and the melting interval from a few to several degrees Celsius [9]. It is chemically inert and rather inexpensive.

An interesting property of paraffin for actuator applications is the volume expansion associated with its phase transitions. When melted, paraffin normally expands 10–20% in volume. The explanation for this is that the alkane chains pack themselves with a relatively high degree of crystallinity in the solid phase, which requires less volume than the disordered formation in the liquid phase.

In addition, liquid paraffin has low compressibility. This is particularly important for actuator applications, and means that most of the volume expansion remains even under high pressures created by large loads. For example, the alkane C\textsubscript{24}H\textsubscript{50} has a 25% volume expansion when heated from room temperature to 100°C; if it is loaded with a pressure of as much as 200 MPa, the expansion is 12%, which is still a large expansion [10].

Furthermore, the non-toxicity and low cost in combination with simple electrical driving by resistive heating, also makes paraffin suitable for applications other than those requiring high pressures.

Finally, the thermal hysteresis of paraffin activation and deactivation is just a few degrees of Celsius [11].

In order to understand and model the actuator material properties, the paraffin needs to be characterized properly. In this work, two methods are used; pressure-volume-temperature (pVT) measurements and differential scanning calorimetry (DSC).
The expansion of paraffin waxes can be characterized by pVT measurements using a dilatometer. Basically, the paraffin sample is placed inside a cylinder, and when the paraffin melts it pushes a piston. The temperature is recorded, and from the displacement of the piston, the volume change can be calculated. The piston is spring loaded and hence the pressure increases when the paraffin expands. A pVT measurement from Paper I on the paraffin used in Papers I–VII, melting at 46–48°C, is shown in Figure 1. As seen in the figure, this paraffin has an expansion of 10% at a pressure just above 12.5 MPa.

To illustrate the thermal behaviour of paraffin, Figure 2 shows the specific heat of the paraffin from a DSC measurement from Paper VI. The hillock peaking at around 25°C is associated with a solid-to-solid phase transition. The large peak with a maximum at 47°C is the solid-to-liquid transformation. The required energy for this transformation is the integral of this peak. This energy is called latent heat, since it is stored in the molten paraffin and released upon solidification. As seen in figure 2, there is a rather large amount of latent heat associated with this transformation. Comparing with the pVT measurement, also the expansion increases rapidly in the temperature intervals of the peaks.

Figure 1. pVT measurement of the paraffin used in Papers I–VII.

Figure 2. DSC measurement on the paraffin in Papers I–VII showing the temperature dependence of the specific heat.
3.2 Modelling paraffin

Paraffin is a material of interest in the area of thermal storage, due to the large amount of latent heat associated with the solid-liquid transformation. In this area, thermal modelling has been made on the thermal properties of paraffin [12–14]. For paraffin microactuators, both analytical and numerical models for the thermal behaviour have been presented [15]. However, for an actuator it is of greater value to make a thermomechanical model that predicts also the speed and amplitude of the actuator displacement. This has not been presented earlier; therefore a thermomechanical model is presented in Paper V in order to better understand the actuator, cf. Section 6.2.4.

The performance of a paraffin actuator is governed by several properties. The thermal conduction and the specific heat capacity, of both the paraffin and the rest of the actuator body, determine how fast the actuator will operate. In addition, the size of the paraffin actuator determines how much thermal energy that is stored as latent heat. Another factor is the influence of the actuator geometry on the thermal transport.

To better understand how all these properties contribute, a software model of the paraffin actuator in a metallic micropump is set up. The simulation software used is based on the finite element method (FEM). The basic working principle of the FEM is that the modelled structure is divided into several smaller pieces. Then, in each piece the constitutive equations of the relevant properties are solved. Finally, the solutions from all the pieces are combined to get the overall behaviour of the modelled structure in terms of, for example, temperature distribution or mechanical strain.

3.3 Characterization of actuators and fluidics

For characterization of the actuators of this thesis, a contact probe is used to measure the deflection. The contact probe can also be loaded with additional mass in order to measure the deflection at different forces. White light interferometry (WLI) is used to measure deflections without a load.

Valves and pumps are characterized with commercial pressure sensors and flow sensors. However, in some cases it is difficult to use a flow sensor. In such cases, the propagation of the liquid is measured by observing the interface between air and liquid visually or recording it with a video camera. Then, from the cross-section area of the channel and the propagation speed, the flow rate is calculated.
4 Fabrication methods

The traditional and most common fabrication method in MST is batch processing of silicon substrates [1]. This includes subtractive techniques like wet and dry etching as well as additive techniques like deposition, *e.g.* sputtering. The most common way of defining the pattern for the subtraction or the addition of material is photolithography.

In the basic photolithography process, the pattern is usually made by depositing a photosensitive polymeric layer, a photoresist, on the surface that is to be processed, then exposing it to ultraviolet (UV) light through a mask. Depending on the type of polymer, the exposed areas are either reinforced or weakened and are either unaffected or removed, respectively, by a developing liquid.

The introduction of new substrate materials like plastics and metals has required – or enabled – new fabrication methods. Metals can be etched by photochemical machining (PCM) in a similar way as silicon. For plastics, injection moulding is a cost-effective production method. In addition, both metals and plastics can be milled and drilled to obtain the desired shape. In many cases, especially for small series and prototypes, this can be easier and cheaper than traditional MST processing. However, this is valid for somewhat larger microstructures. For the smallest microstructures, the resolution of mechanical precision machining is not sufficient.

Here follow the fabrication methods used in the work of this thesis.

4.1 Printed circuit board technology (Papers I–VII)

Printed circuit board (PCB) technology can be used to build microsystems including microfluidics [16]. The technology is originally used for making substrates that hold and interconnect ICs and other electronic components. A PCB consists of a carrier substrate (often glass fibre reinforced epoxy) laminated with a thin conducting layer (often copper) on one or both sides. The conducting layer is then patterned to create circuit paths. This is done either by photolithography with subsequent etching, or by milling. The outer contour of the substrate is often milled and through-holes for connection vias to the other side of the substrate are drilled. A flexible printed circuit board (FPC) is a PCB with a thin and flexible substrate (often polyimide) and is often used for a more flexible assembly of compact electronic equipment.
In this thesis work, PCBs are used as a structural material or as heater substrates and FPCs are used for integrable heaters.

4.2 Rapid prototyping using epoxy  
(Papers I, IV and VII)

Epoxy is an example of a polymer that can be selectively cured by UV light. Epoxies of this group are often used as photoresists. In addition, they can be used for building microstructures. The photolithography of liquid epoxy is a rather fast way of making prototypes. Hence, epoxy is used in different kinds of rapid prototyping processes using liquid photopolymerization [17, 18].

In Papers I and IV, the liquid photopolymerization process is adapted for fabrication of structures on both sides of an FPC. Inner structures are defined by selective curing, and the outer shape is defined by a mould. Figure 3 shows an example of this process. In Paper VII, the process was adapted for moulding of the whole structure directly on a PCB substrate, Figure 4.

For getting fast feedback on new designs, rapid prototyping is a very effective fabrication method.

Figure 3. Cross-section showing an example of rapid prototyping of epoxy on an FPC. (1) The FPC is first placed in the mould. Then, uncured epoxy is added and masks are clamped on both sides of the mould. (2) The epoxy is selectively cured through the masks from both sides. (3) Uncured epoxy is rinsed off, leaving the completed structure.
Figure 4. Cross-section showing an example of rapid prototyping of epoxy on a PCB. (1) Uncured epoxy is placed in a polydimethylsiloxane (PDMS) mould and the PCB is clamped on-top. (2) First, excessive epoxy is cured from the PCB side, and then epoxy is cured through the PDMS mould. (3) Finally, the mould is removed.

4.3 Precision machining (Paper III)

As previously stated, it is not always necessary to use traditional batch processing microstructure technology for manufacturing the microsystems. Sometimes precision lathe machining, drilling or milling are better and simpler ways of making certain parts of the system or component. This is the case for the size and geometry of the parts for the actuator in Paper III. Figure 5 shows examples of parts that are made by precision lathe machining.

Figure 5. Components made by precision machining, placed on a matchstick.
In this thesis work, filling of liquid paraffin is the standard method for introducing the paraffin into the actuators. However, in the work of Paper III, the assembly of parts is made manually. Ultimately, for mass production purposes, it is possible to use pick-and-place robots. To this end, the paraffin is introduced as a solid plug coated with silicone. Such a method can potentially be incorporated in a pick-and-place assembly line.

4.4 Layered metallic structures (Papers V and VI)

In Papers V and VI the main structural material is metal stencils, bonded together by a thin film of the polymer parylene [19]. An example of a stacking order of different layers is shown in Figure 6. Also, FPC and polymeric membrane layers can be added. All layers are first coated with parylene, then stacked and clamped together followed by a heat treatment resulting in a bonded structure.

The metal sheets are made in the same way as stencils used as solder masks for PCBs. These are made of stainless steel, and the desired structures are defined by PCM [20], i.e. photolithography and wet etching of metal sheets.

This bonding process has potential for batch processing of large surfaces, i.e. simultaneous processing of a large number of structures.

Figure 6. Example of stacking order for parylene bonded layers. (1), (2) stainless steel layers for a channel structure, (3) polymeric membrane layer, (4), (5), (7), (8) stainless steel layers for an actuator structure, and (6) FPC with resistive heater circuits.
Microactuators are the “muscles” of microsystems. Hence, they are vital parts of many microsystems, and provide the movements and the forces needed to move fluids or mechanical parts in the system. In this section, the field of microactuators is explored.

5.1 Actuator materials

There are several materials that can be used for actuation [21]. Materials that have a piezoelectric effect are one example of this. These materials expand or retract when they are subjected to an electrical field. Another example is the shape memory alloys (SMAs), which can “remember” their original shape and return to it after deformation, by adding thermal energy. Examples of other thermally activated phase changing materials (PCMs) are those changing from solid or liquid to gas (thermopneumatic) or from solid to liquid (thermohydraulic).

One of the best ways of comparing the performance of different actuators is to look at the energy density of the actuator material. The energy density is proportional to the maximum strain achievable from the material times its maximum achievable stress, divided by its volume [22]. Energy density becomes particularly important when miniaturizing actuators, as the total volume of an actuator needs to be effectively utilized.

If considering the top three materials in this comparison the SMAs have the highest energy density due to capability of both large strains (10%) and high stresses (hundreds of megapascals). The paraffin PCM comes second, also having large strain and stress capability. Piezoelectric materials can often exert higher pressures than PCMs. However, their low strains of a few per mille result in a much lower energy density than for PCMs.

At a first glance, SMAs seem to be the best choice. However, this material has to be pre-treated in a particular scheme with strain and heat to obtain the memory effect. The thermal hysteresis of SMAs is typically tens of degrees Celsius, and the integration into microsystems is often complex. Nonetheless, SMA actuators are interesting due to their large strain and stress capability.
In conclusion, paraffin seems to be promising for microactuators due to its high energy density, in combination with its favourable material properties mentioned above.

5.2 Paraffin microactuators

The earliest reports of paraffin microactuators are from the late 1990’s [23]. Since then, several paraffin microactuators have been presented [22–29]. Paraffin actuators have also been used in various valves for microfluidics [30, 31]. A gas valve for satellite propulsion has been reported in [32]. Motorola has reported research on a paraffin in-channel valve for liquids [33]. Another company that has reported research on paraffin microvalves is NanoSpace AB [34].

Regarding the material properties of paraffin in microactuators, a few papers have been presented: Paraffin has been mixed with PDMS for simpler fabrication [35]. It has also been mixed with a carbon powder to enable resistive heating and to make the fabrication process easier [36]. Pure n-alkanes have been mixed in order to achieve a binary expansion mode [37].

As seen above, a few paraffin microactuators had been reported at the outset of this thesis work. However, there were important factors missing for a full understanding of these actuators. Here follows a summary of Papers I-III and the search for some of these factors.

5.2.1 Polymeric actuators (Paper I)

**Background**

One of the most basic microactuators is the membrane or diaphragm actuator. Here, the deflection of the actuator material is directed towards a membrane which transfers the mechanical energy further into the system.

The work of Paper I is the earliest of this thesis. Polymer-based membrane microactuators are interesting in low-cost applications. Previously, very few such actuators driven by paraffin with integrated heaters had been presented. Hence, in order to get valuable design input for future applications, there was an apparent need to evaluate their performance. The actuator in Paper I is a further development of an PCB based actuator presented in [38].

**Results**

In Paper I, paraffin is used in a membrane actuator with an immersed heater. By placing the heater within the paraffin-filled cavity, the thermal losses can be reduced as the paraffin itself acts as a thermal insulator near the walls, as
long as it is not melted and subjected to convection. Figure 7 shows the actuation principle.

The actuator chips are fabricated by the rapid prototyping process for epoxy described earlier. A chip with three actuators is shown both in an exploded view and as an actual chip in Figure 8. Figure 9 shows the actuator deflection measured by a contact probe applying a load of around 0.5 N. Three actuation voltages are used: 0.33, 0.55, and 0.86 V, all at 0.1 Hz. For the highest voltages, the total stroke decreases with time which is an ageing effect that does not appear at lower voltages. Actuation at different frequencies, 0.03, 0.12 and 0.50 Hz, at 1 V is seen in Figure 10. Even at 0.5 Hz, the actuator stroke is 5 μm and useful for, e.g., pump applications.

**Figure 7.** Cross-section showing the actuation principle of a paraffin membrane actuator. First, the heaters are inactive and the paraffin is solid (left). When the heaters are activated, the paraffin melts and expands (right). When the heater is turned off, the paraffin cools and returns to the initial solid state.

**Figure 8.** To the left is an exploded view of the actuator chip containing three paraffin actuators with immersed heaters, epoxy backing and polymeric membrane. To the right is a completed chip with heater FPC visible through the epoxy and the membrane.
Figure 9. Actuator stroke increasing with applied voltages of 0.33, 0.55 and 0.86 V at 0.1 Hz.

Figure 10. Actuator stroke at 0.03, 0.12 and 0.50 Hz at 1 V, decreasing with increasing frequency (from Paper I).

This actuator allowed basic performance testing of a paraffin microactuator by means of a fast and simple fabrication process. This information was needed for further work on paraffin actuation.
5.2.2 Multi-stable actuators (Paper II)

Background
Interesting information of the paraffin properties was obtained from the work resulting in Paper I. One thing was that, if the heating power was too low, the paraffin volume melted only locally in the actuator. This is caused by the low thermal conductivity and the large amount of latent heat required for melting the paraffin. Such a poor temperature distribution is normally seen as disadvantageous for the speed of a thermal actuator. In Paper II, the objective was to evaluate how these thermal properties could be turned into an advantage.

Results
The basic paraffin actuator and many other actuators are non-stable, in the sense that they need a continuous feed of power to remain in a certain position. In Paper II the paraffin itself is used to achieve multiple stable deflection states for a membrane actuator. Basically, by controlling the direction of the solidification, paraffin can be accumulated where the solidification starts, i.e. where the temperature is the lowest. Hence, after full solidification, the distribution of the paraffin volume is shifted inside the actuator body. This gives a certain shape of the actuator membrane that is stable without adding thermal energy. By using several heaters with variable heating power, the starting point of the solidification can be shifted. Hence, the shape of the membrane can be changed between several stable states.

The principle of operation is exemplified with positioning of a mirror, Figure 11. The mirror is used to position a laser beam in order to measure the tilting angles at different stable states.

A device with heaters divided in four heating areas, and the assembled actuator with a mirror is seen in Figure 12. The actuator has a PCB backing with heaters, another PCB defines the paraffin volume and the paraffin is sealed by a membrane. The mirror is then attached to the membrane on a rubber post.

The conclusion is that by simply adding more heating zones, paraffin actuators can have multiple stable deflection states that require neither addition of energy nor mechanical parts.

The actuator presented here adds to the functionality of paraffin actuators. In some cases, it can replace large electromagnetic actuators to both decrease size and power consumption. In addition, the simple drive of the actuator suggests that, in some applications, it could replace piezoelectric actuators with complex drive units.
Figure 11. Cross-section view showing the actuation principle for achieving stable states. (a) The solid paraffin (grey) and the mirror in a plane position. (b) All the paraffin is melted (white) and (c) half of the heating zones are switched off. The paraffin solidifies in the unheated areas, starting farthest away from the heated zones while molten paraffin is transported to the solidification front. (d) All heaters are switched off and the solidification proceeds through the rest of the paraffin. As a result of the material transport the mirror is now tilted by the membrane.

Figure 12. The actuator design without paraffin and membrane, showing the four heater zones (left), and the assembled actuator with a 2 x 2 cm² mirror (right).

5.2.3 Metallic piston actuators (Paper III)

Background

Microactuators have great potential in applications where space is limited. A really strong actuator can be made smaller, while still delivering a useful force. The objective of Paper III was to increase the force and stroke compared with those in Paper I, as well as to investigate the hysteresis in high performance positioning.

Previous papers used polymers as the structural material. These investigations indicated that a higher bulk modulus was needed in order to better utilize the force of the expanding paraffin. In Paper III, metal was investigated for this purpose.
In some cases, it is preferable to use a piston instead of a membrane to transfer the stroke and force of the paraffin expansion. One application for the actuator in this work was positioning of the mirror segments of a satellite-based telescope, which is under development by NASA.

In general, strong, long-stroke piston microactuators are expected to find use in a multitude of MST applications, for instance in positioning, switches, valves, microhydraulics and microdispensing.

**Results**

To build the actuator, paraffin is enclosed between a backing lid and a piston inside a cylinder, Figure 13. To prevent leakage, the paraffin is coated with a thin silicone elastomer. Consequently, the paraffin is essentially encapsulated inside a highly flexible “balloon”, which prevents leakage when the paraffin is molten.

The fabrication of the titanium parts is made by precision machining, described in the fabrication section. First, the piston is placed inside the cylinder, and then the paraffin is inserted as a solid plug inside the cylinder. Finally, the lid is glued onto the end of cylinder.

The assembled actuator is shown in Figure 14. The unloaded maximum stroke is 140 μm. Also, it has relatively low hysteresis for the 0.5 N load, Figure 15. The maximum force tested was 10 N.

![Figure 13. Schematic of the piston actuator.](image)

![Figure 14. Piston actuator with connection wires.](image)
Figure 15. Deflection of the piston actuator versus input power for three different loads. The deflection at 0.5 N shows the low hysteresis between activation (up) and deactivation (down).

This work shows that piston type paraffin microactuators can be utilized for large forces, and that paraffin leakage between sliding microparts can be prevented by a flexible encapsulation of the paraffin. Also, low actuation hysteresis is shown in such a device.
6 Micropumps

In order to control the flow on a microfluidic chip, different kinds of valves are needed. Valves can be operated by the fluid itself (passive valves) or by an actuator (active valves) [39]. Furthermore, a valve is classified as normally open or normally closed, depending on which state it is stable in, i.e. the state that it does not require energy to maintain. A third class is bi-stable valves that are stable in both open and closed state.

Another interesting application area of actuators in microfluidics is micropumps. Here, the actuator can be used to displace fluid in a pump chamber. In combination with passive or active valves, or even without valves, a net-flow can be achieved.

Micropumps are often classified as either mechanical or non-mechanical. Mechanical pumps use various kinds of moving parts to displace the fluid, while non-mechanical pumps have no moving parts but instead typically use magnetism or electrical potentials to manipulate the fluid [40].

Traditional mechanical pump principles in macro scale, using for example rotating parts or moving pistons, become more ineffective as the size of a pump is reduced. The main reason is that the friction between moving parts becomes relatively large in small systems. For pistons, there are difficulties with sealing, even if there are examples where this has been accomplished [41]. Another reason is manufacturing difficulties, as a micropump is typically smaller than a cubic centimetre. Instead, micropumps often use membranes to displace the fluid [40].

If the trend is that the microfluidic systems are decreasing in size and the fluid volumes on-chip decrease, so will also the required flow rates in many cases. If the microfluidic systems are to be self-contained in order to get true μTAS chips, the pre-treatment steps, including filtration of samples, would have to be integrated on-chip. Narrower channels due to space requirements and integration of filters most often increase the back-pressure in the fluidic systems. In accordance with Poiseuille's law, in which the pressure is proportional to the inverse quartic of the radius, a decrease in channel radius by a factor of 2 increases the pressure drop in the channel by a factor of 16! In addition, some separation and analysis techniques demand higher pressures to increase performance, e.g., on-chip high performance liquid chromatography [42].

The conclusion is that some trends point towards a need for pumps capable of delivering high pressures while the demands on a high flow rate are
secondary. However, a high flow rate will still be important for many applications, like dispensers for mass spectrometry and ink-jet dispensers, even if the total volumes are small.

### 6.1 Comparison of micropumps

There are many actuation principles available for micropumps, as seen in recent reviews [40, 43]. Figure 16 illustrates the current status of micropumps in terms of achievable pressure and flow rate with respect to actuation principle. For really high pressures, in the order of megapascals, there are currently only a few relevant actuation principles. The principle of electroosmotic (EO) flow currently seems to have the greatest potential. EO is a non-mechanical pump principle that basically works by inducing and moving charged areas in the liquid. However, EO sets particular demands on the pumped liquid. One demand is that it has to be polar or polarisable in order to achieve charged areas [44]. Also, the voltages for driving the pump at high pressures are very high, often in the kilovolt-range. In addition, since gases cannot be pumped, the pump cannot fill itself with liquid from an initially empty state (self-priming).

![Figure 16. Comparison of micropumps regarding maximum flow rate and maximum pressure based on [40] and [43]. The different actuation principles are: EM – electromagnetic, PE – piezoelectric, ED – electrohydrodynamic, P – pneumatic, TP – thermopneumatic, and EO – electroosmotic. The potential area for paraffin (thermohydraulic) is also shown.](image)

Paraffin has been presented earlier as having a large potential for high pressures and large strokes, which is often a desirable combination for micro-
pumps. The area where paraffin micropumps are believed to have great potential is marked in Figure 16. The prediction is based on the fact that paraffin can withstand high pressures without being compressed much, as is discussed in the material properties section of this thesis. Paraffin micropumps are, however, predicted to have a lower flow rate than many other mechanical micropumps due to the relatively low actuation frequency of paraffin actuators.

6.2 Paraffin micropumps

At the beginning of the work presented in this thesis, there were few, if any, reports of paraffin actuated micropumps. However, as discussed above they have great potential for microfluidic systems.

Hence, in order to evaluate the validity of the prediction of high-pressure capabilities, as well as general performance, such micropumps are investigated in this thesis work. A summary is presented in the following.

6.2.1 Polymeric micropumps (Paper IV)  

Background
In the work of Paper IV, the membrane actuators from Paper I are combined with a fluidic channel structure in order to build a micropump. The aim is to accomplish an on-chip micropump for low-cost applications, as well as to obtain design and performance parameters for further work on high-pressure micropumps.

Results
The resulting pump has active valves at its inlet and outlet, and a pump chamber, each driven by a membrane actuator, Figure 17.

By driving all three actuators in a suitable sequence, Figure 18, a net flow can be achieved.

The channel structure is fabricated using rapid prototyping of epoxy, as described in the fabrication section of this thesis. It is structured on a thin glass substrate and bonded to the actuator chip using the same type of epoxy as in the channel structure and the actuator chip.

The pump with silicone tubes and a special connection for high pressures is seen in Figure 19. The valves sustain a pressure of 0.9 MPa and the pump can achieve flow rates of 75 nL/min at 0.03 Hz.

This paper is one of the first reports on a paraffin driven micropump. In addition, it has pressure capabilities that compare well to other micropumps. The study also explores the mechanical strength limitations of a polymeric pump housing in high-pressure MST applications. Also, it is the basis for a new materials choice in Paper V.
Figure 17. Cross-section of the symmetrical design of the micropump. The pump chamber is in the middle, flanked by the inlet and outlet valves, each operated by the actuator from Paper I.

Figure 18. Driving sequence of the pump, inlet and outlet actuator, repeating after 6/6 of the period time. The net flow from the valves is zero and the total flow corresponds to the stroke volume of the pump actuator.

Figure 19. To the left: the micropump showed from the actuator side with rubber connection tubes visible from the channel side. To the right: side view of the micropump with a special connection port for high pressures mounted on the channel side.
6.2.2 Metallic micropumps (Paper V)

**Background**

Paper V describes a micropump in which the design from the polymeric micropump in Paper IV has been adapted for using stainless steel, instead of epoxy, as actuator body. The aim was to increase both speed and pressure capability of the pump. Steel has a higher thermal conductivity than epoxy which can enable faster paraffin actuators. In addition, its bulk modulus is higher which makes it simpler to design a pump for higher pressures.

**Results**

The pump structure was made by bonding metal layers as described in the fabrication section. The resulting micropump, and the fixture that was used for clamping and fluidic connections, are shown in Figure 20.

The pump was tested with water and reached pressures above 5 MPa, Figure 21, at a constant flow rate of 0.75 μL/min. At low pressure, the pump reaches a maximum flow rate of 1 μL/min at 0.2 Hz.

Using metal as main structural material, instead of a polymer, increased both the flow rate and the pressure. Currently, this is probably the strongest mechanical micropump reported in total size below one cubic centimetre. In addition, it compares well to the high pressures of the strongest electroosmotic (i.e. non-mechanical) micropumps. Chen et al., for instance, report a back-pressure of 26 MPa [45], which is currently one of the highest pressures among micropumps in general.

![Figure 20. To the left: the metallic micropump. To the right: the micropump mounted in its clamping fixture with two fluid connection ports with tubes.](image-url)
6.2.3 Thermomechanical pump model (Paper V)

**Background**
As stated above, the thermal behaviour of paraffin has been modelled previously. However, for actuator applications the mechanical properties are important as well. In order to better understand the actuator and the pump behaviour, a thermomechanical FEM model is presented in Paper V. The model takes into account the thermal properties of the paraffin, the temperature dependence of its expansion and the driving waveform of its heaters.

**Results**
The modelled pump actuator displacement is shown in Figure 22 for three frequencies. At 0.37 Hz, the displacement is just about to saturate while it is almost fully saturated at 1.11 Hz. The saturation behaviour of the modelled displacement resembles that of the measured displacement in Paper I.

The modelled and the measured frequency dependence of the flow rate are shown in Figure 23. The model predicts a higher flow rate than what was actually observed. By also modelling the valve actuators, it was clear that for higher frequencies, the valves cannot close fast enough, using the current waveform for driving them. Hence, above a critical frequency, the pump starts to leak and the flow rate is reduced. By using this model, the driving waveform can be adjusted in order to allow higher pump frequencies without leakage, which would result in higher flow rates.
The model also gives information about the temperature distribution in the actuator. The temperature distribution at around 0.2 Hz, where the maximum flow rate was measured, is shown in Figure 24. This result indicates that the temperature is rather low above the actuator membrane where the pumped liquid is flowing. This is particularly interesting when pumping heat sensitive liquids.

![Figure 22. Modeled pump actuator stroke for three different frequencies. The stroke at 0.14 Hz clearly saturates.](image)

![Figure 23. Modeled and measured frequency dependence of the flow rate.](image)
6.2.4 Metallic microdispensers (Paper VI)

Background

Paper VI investigates dispensing of liquid at high pressures and continuous flow, using paraffin actuation. One possible application is sample injection in on-chip chromatography. Also, characterizing the flow performance of a paraffin dispenser increases the understanding of paraffin actuation, since the flow is proportional to the derivative of the actuator stroke.

Results

The pump from Paper V is here provided with a larger pump actuator to allow for a larger volume per stroke, Figure 25. One reason for this is to reduce the influence of the outlet actuator stroke on the total flow.

The flow is characterized for two devices, D1 and D2. Figure 26 shows dispensing at 0.6–2 MPa of back-pressure, and Figure 27 shows dispensing of the target volumes (1) 350 nL and (2) 540 nL.

The dispensers push water against relatively high back-pressures, without any pressure dependence. They also show good repeatability of the dispensed volume. In addition, it is found that predictions of the flow characteristics can be made, at least qualitatively, from the specific heat of the paraffin, cf. Figure 2 and 26. This is valuable information, since the specific heat can be measured rather easily by differential scanning calorimetry (DSC).

Figure 25. Cross-sectional view of the dispenser. The fluidic channel is dark/black and the paraffin is white.
Figure 26. The average dispensing characteristics for devices D1 and D2, at 0.6, 1.3, 1.6 and 2.0 MPa of back-pressure. The maximum difference between the different pressures is shown at every ten point.

Figure 27. Integrated volumes for the controlled dispensing of target volumes. Top to bottom at maximum: D2 volume 2, D1 volume 2, D2 volume 1 and D1 volume 1. The deviation between the pressures is shown at every ten point.
6.2.5 Polymeric on-chip dispensers (Paper VII)

Background
Strong on-chip pumps may increase the performance of LOC systems. The objective of the work reported in Paper VII is to evaluate how paraffin pumps can be integrated on-chip.

Results
The resulting dispenser has a paraffin chamber, a liquid reservoir and check valve, Figure 28. The valve has an integrated port for filling the reservoir with a liquid using a syringe. The function of this valve is described schematically in Figure 29. Basically, the rubber valve work as a septum for a syringe needle, i.e., it can be penetrated by a needle, and when this is removed, the rubber flexes back and seals the penetration hole.

After filling, the rubber plug works as a normally closed valve. Hence, the rubber plug serves a dual purpose: septum and valve cap. In the fabrication, the rubber plug is fastened in a compressed state against the valve seat. The residual stress in the plug determines the pressure at which the valve will open. Then, during actuation, the heater starts to melt the paraffin which expands and pressurizes the liquid to be dispensed. When the opening pressure is reached, the valve opens and the liquid is ejected. After the dispensing is completed, the heater is switched off and the paraffin starts to cool down and retract. The volume of the paraffin is now decreasing which causes a negative pressure that closes the valve. Hence, liquid is prevented from leaking back into the reservoir.

Figure 28. Dispenser unit with an empty liquid compartment between the paraffin volume and the valve plug leading to the channel.
Figure 29. Function principle of the valve plug. (a) Liquid filled through the Interface plug with a syringe. (b) An increased pressure in the liquid on the left side causes the plug to deflect and open. (c) A negative pressure from the left side causes the plug to shut tight against the valve seat.

For the LOC application, three dispensers are integrated into a chip together with a channel system. The chip was fabricated by rapid prototyping of epoxy onto a PCB heater substrate, described in the fabrication section. A lid was bonded onto the epoxy structure and finally the valve plugs were attached. The parts of the chip are presented in Figure 30.

The function of the completed chip was tested by filling the three reservoirs with coloured and uncoloured water, and sequentially injecting them into the channel system by activating the paraffin dispensers one by one. An injection sequence is shown in Figure 31. The liquids are separated from each other in the channel by small air gaps to increase the rinsing efficiency and prevent mixing.

The opening pressure of the valves is 12–286 kPa. The typical flow rate is around 12 μL/min, when the paraffin is actuated with 1.6 W of heating power.

This work demonstrates that paraffin can be used for effective on-chip driving of liquids, hence eliminating the need for cumbersome external pumps in many applications.
Figure 30. (a) Exploded view of the dispenser chip. (b) Schematic showing the different parts of the chip.

Figure 31. Dispenser sequence on the chip. The channel is first filled with colored water. The first dispenser to the right is activated and starts to push clear water into the channel (a) and filling the whole channel (b). The middle dispenser is activated (c) and pushes colored water and the air gap all the way through to the waste (d). Finally, the left dispenser is activated (e) and fills the channel with clear water (f).
7 Discussion and conclusion

Paraffin possesses a rare property among actuator materials: it combines high force with long stroke. However, the low thermal conductivity and the high specific heat in paraffin makes actuators based on this material rather slow, compared with other actuator types. Important here is to utilize the paraffin in the right manner. First of all, paraffin is most suitable for systems where speed is of less importance. Its speed is linked to thermal transport. A really fast paraffin actuator would need a lot of heating power and active cooling, resulting in a high power consumption. In applications like battery powered devices, where the energy supply is limited, this may be a problem. By using a proper design in combination with the right construction materials, a system dependent trade-off between power consumption and speed can be reached.

For thermal actuators, cooling is often the most important factor determining the speed. Supplying enough heat into the actuator material is seldom a problem; this can be done by central, or even distributed, heaters by simply increasing the heating power. Cooling, however, is limited by the rate of thermal transport away from the actuator. This is determined by the thermal properties of the material and the design, as well as on the ambient properties, e.g. distance to heat sinks and use of active cooling. Another important factor is convection in the liquid phase, which is much larger than the thermal diffusion in solid paraffin.

The geometry and material influence on cooling of a body can be illustrated by using Newton’s law of external heat transfer and the normal component of heat flow. Combining these gives the time dependence of the heat transfer in a body. The temperature as a function of time, T(t), of the body can be written as:

\[ T(t) = \Delta T \cdot e^{-k \cdot t} + T_0, \]

where \( \Delta T \) is the decrease in temperature, \( k \) is a geometry and material constant, \( t \) is the elapsed time, and \( T_0 \) is the surrounding temperature. The interesting factor here is the geometry and design constant:
where \( \frac{A}{V} \) is the area-to-volume ratio of the body and therefore design dependent, while the heat transfer number \( \alpha \), the density \( \rho \), and the specific heat capacity \( c \) are material parameters. Hence, increasing \( \frac{A}{V} \) and \( \alpha \) or decreasing \( c \) and \( \rho \) (or mass, \( \rho \cdot V \)), will result in a faster actuator. In this way, even paraffin actuators can become relatively fast. In fact, for small paraffin microactuators frequencies of up to 300 Hz have been reported [30]. The paraffin part of the actuator in this case has a diameter of 400 \( \mu \)m and is 9 \( \mu \)m high.

So far, the pressures have not been high enough to significantly affect the paraffin properties. Hence, the complexity of the model in Paper V can be kept at a relatively low level. However, if the pressure is increased, there will probably be necessary to model its interaction with both the solid and the liquid state of the melting paraffin. Examples of interesting properties that can be evaluated further are the mechanical strain in the solid part of the paraffin, hydrostatic pressure and convection in the liquid part, as well as the propagation of the solid-liquid interface. Ultimately, at several tens of mega-pascals and above, the pressure dependence of the melting point will be of increasing interest.

This work has been about exploring paraffin as a microactuator material in designing, fabricating and evaluating new components and systems. It is important to remember that using new fabrication processes to make new systems increases the complexity of the task enormously. The development of new components or systems alone is often complex enough. Hence, existing processes have been adapted – when possible – for the designs in order to reach the aims.

The pressure limiting factor is the encapsulation of the paraffin, or other parts of the system, not being able to sustain the high pressure induced by the paraffin. In the work of this thesis, this is indicated by leakage of paraffin under the membrane or leakage of the pressurized water from the channels. Hence, the limitation of the paraffin with respect to pressure has not yet been reached in microactuator applications.

In this thesis work, paraffin is mainly introduced into the actuator body by filling of molten paraffin into designated cavities. However, air pockets and air content in the paraffin can reduce the actuator performance tremendously. Hence, this has to be considered when designing the paraffin cavities, and when filling them.

Dispensing is an established back-end production method for adhesives and solder paste. Hence, it can potentially be adapted for dispensing paraffin in serial production of actuators.
At some critical size when scaling down, there may be a need to go from filling molten paraffin into the actuator, to a process more suitable for smaller dimension. For the small and relatively fast actuators in [30] the paraffin is thermally evaporated and dry etched, which may be a good fabrication process for the paraffin in the smallest actuators.

7.1 Comparison of micropumps revisited

Looking back at the pump comparison in Section 6.1, the paraffin micropumps in Papers IV–VII can now be compared. This can be made by using the pump efficiency factor, $E$, calculated from:

$$E = \frac{Q_{\text{max}} \cdot p_{\text{max}}}{2P_{\text{in}}},$$

where $Q_{\text{max}}$ is the maximum flow rate at zero pressure, $p_{\text{max}}$ is the maximum pressure resulting in zero flow rate and $P_{\text{in}}$ is the input power.

The characteristics of the paraffin pumps are presented in Table 1. For comparison with relatively strong micropumps driven by other actuator materials, the order of magnitude of the pump efficiency are typically $10^{-6}$–$10^{-5}$ for thermopneumatic, $10^{-5}$–$10^{-4}$ for electroosmotic and $10^{-3}$–$10^{-2}$ for piezoelectric actuation [2, 40, 43].

Table 1. Comparison of the micropumps of this thesis*.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Material</th>
<th>Mode</th>
<th>$Q_{\text{max}}$ (μL/min)</th>
<th>$p_{\text{max}}$ (MPa)</th>
<th>$P_{\text{in}}$ (W)</th>
<th>$E$ (μW/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>Polymer</td>
<td>Cyclic</td>
<td>0.08</td>
<td>0.9</td>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>V</td>
<td>Metal</td>
<td>Cyclic</td>
<td>1</td>
<td>5</td>
<td>1.1</td>
<td>38</td>
</tr>
<tr>
<td>VI</td>
<td>Polymer</td>
<td>Dispenser</td>
<td>12</td>
<td>0.3</td>
<td>1.6</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Burst**</td>
<td>240</td>
<td></td>
<td></td>
<td>358</td>
</tr>
<tr>
<td>VII</td>
<td>Metal</td>
<td>Dispenser</td>
<td>1.4</td>
<td>2.3</td>
<td>1.1</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cyclic</td>
<td>2.4</td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pulse***</td>
<td>&gt; 8</td>
<td></td>
<td></td>
<td>135</td>
</tr>
</tbody>
</table>

* $Q_{\text{max}}$ – maximum flow rate, $p_{\text{max}}$ – maximum pressure, $P_{\text{in}}$ – input power and $E$ – pump efficiency.

** Burst mode is when a valve opens at a high pressure resulting in an initially high flow rate.

*** Pulse mode is when the dispensing actuator is fully actuated at once as opposed to the smoother actuation in normal mode.

From the table, it can be noted that the burst mode of the polymeric on-chip dispenser and the pulse mode of the metallic dispenser has the highest efficiency. However, these modes only last for a few seconds. For longer periods, the cyclic mode of the metallic pump and dispenser has the highest efficiency.
For the metallic dispenser, the presented pressure does not result in any change in flow rate. Hence, it is not a true maximum. In the other cases, the maximum pressure depends on the strength of the device structure, not on the paraffin.

In conclusion, the pump efficiency for these paraffin micropumps is in the order of $10^{-5}$–$10^{-4}$. Compared with thermopneumatic pumps, i.e. another thermal actuation principle, the paraffin micropumps seem better. Paraffin-based micropumps compare well with electroosmotic pumps, also having high pressure capabilities. However, paraffin cannot compete with the efficiency of piezoelectric micropumps. The piezoelectric actuation is capable of very high flow rates and moderate pressures at relatively low power consumption, giving them their high pump efficiency ratio.

It should be noted that if either the flow rate or the pressure of a certain pump is insufficient for an application, it does not matter if its efficiency is high. Hence, this efficiency factor has to be used with caution and as a complement to other comparison factors.

### 7.2 Fulfilment of aims

Going back to the aims presented in the introduction, the following have been accomplished in this thesis work:

- This work has evaluated designs, fabrication methods and materials, as well as speed, displacement and pressure capabilities of paraffin actuation in actuators, valves and pumps.

- The low compressibility of paraffin in combination with its large expansion is suitable for applications that need very high pressures (several megapascals). The upper limit of paraffin with respect to pressure is still to be reached by improved designs.

  However, since the actuation is rather slow due to the thermal properties, applications with moderate demands on actuation speed can benefit most from using paraffin actuation. One example is microhydraulics, where the pressure build-up may be slow while the actual actuation in the hydraulic output can be made rather fast. Another example is biomedical applications where paraffin could be used for dispensing samples on-chip or possibly in high-pressure applications like miniaturized high performance liquid chromatography (HPLC).

  In addition, the low thermal hysteresis of paraffin results in low actuation hysteresis, which is important in applications like positioning.
- Low thermal conductivity and high specific heat limit the speed and effective stroke, but is turned into an advantage by using directional solidification and hence enabling a multi-stable actuator.

The hypothesis of paraffin being suitable for pumping liquids at high pressures and low flow rates holds to be true.
8 Outlook

Two of the applications mentioned earlier – microhydraulics and high-pressure biomedical applications – seem especially interesting to work further on. This is mainly because there are very few examples of micropumps that can show true high-pressure capabilities in terms of controlling (e.g. valves) and driving (e.g. pumps) microfluidics, while paraffin has in fact shown this capability in this thesis work. Consequently, in such applications, paraffin deserves to be treated as a promising alternative to other actuator materials. Also, as a promising actuator material, it needs to be evaluated further. For example, future research should include optimized drive and control of paraffin actuators, as well as an improved paraffin model.

In my own view, the greatest explicit achievement of this work is the high pressure obtained with the metallic micropump. Looking more generally, I hope that this work can in some way contribute to an increased understanding of, and interest in, paraffin as an actuator material. It would be very satisfying to see actual commercial use of paraffin in microactuators, and I believe we will see this in the future.
Området som denna avhandling behandlar ligger inom mikrosystemteknik (MST). MST handlar i grova drag om att miniatyrisera system eller dess komponenter. Mikro står vanligen för mikrometer, en miljondels meter, vilket för en eller flera dimensioner ofta är det behändigaste måttet på strukturer som ingår i dessa system.


En utmaning inom mikrofluidiken är att bygga pumpar som kan integreras direkt i det lilla chippet. Detta är mycket effektivare än en större extern pump som ansluts med relativt långa slangar. Dagens integrerbara små pumpar kan lätt transportera vätska och gas på chippen. Men i slutänden behövs ofta filtrering och separation för att få fram de prover som ska analyseras. Trånga kanaler och filter medför då ett flödesmotstånd som många pumpar har problem med att klara.

Området inom MST för denna avhandling är mikroaktuatorer och mikropumpar. Aktuatorer är de komponenter i ett mikrosystem som skapar rörelser och kan alltså ses som motorer. Aktuatorer används till exempel i de pumpar som förflyttar vätska i ett chip för mikrofluidik.

Avhandlingens första artikel, Paper I, utvärderar paraffin i en av de enklaste aktuatortyperna; membranaktuator. I denna aktuator riktas hela volymexpansionen mot ett membran som då böjs ut och det är denna rörelse som sedan utnyttjas vidare. Aktuator byggdes i plast och dess utvärdering utgjorde sedan grunden för utvecklingen av pumparna i Paper IV, V och VI.


Paper III handlar om att bygga en paraffinaktuator i metall där membranet bytts mot en kolv. Detta gör aktuator starkare när krafterna behöver vara ännu mera riktade än i fallet med ett membran. Projektet finansierades av NASA och en tänkt tillämpning var riktning av teleskopspeglar i satelliter.

Paper IV presenterar en pump i plast som byggdes med aktuator i Paper I. Tre sådana membranaktuatorer sitter på rad och klämmer fram vätska genom att aktiveras i en viss sekvens som sedan återupprepas. Denna pump klarar höga tryck jämfört med andra sorters pumpar men lämpar sig bäst för pumping av väldigt små volymer.

Som nämnts ovan så är det de termiska egenskaperna som gör paraffinet långsamt. Membranet måste röra sig upp och ner för att pumpa vätskan. Hastigheten för detta begränsas främst av hur snabbt man kyler för att få paraffinet att stelna och därmed få membranet att gå tillbaka.

Pumpen i Paper VI har fått en större pumpkammare än den i Paper V. Den stora pumpkammaren kan aktiveras långsamt för att få ett oavbrutet flöde av en viss volym till skillnad från det stötvisa flödet som de tidigare beskrivna pumparna ger. Denna pump ses i figuren nedan.

Slutligen presenteras ett analyschip av plast i Paper VII. Detta chip innehåller tre pumpar för oavbrutet flöde. Dessa kan aktiveras i en sekvens för att föra prov och analysvätskor till en kammare på chippet för diverse reaktioner samt analyser.

Även om en av världens starkaste mikropump presenteras här så uppnådes inte paraffinets begränsningar gällande tryck. Denna begränsning återstår alltså att försöka nå, inte som ett självändamål; utan för att kunna utnyttja paraffinet maximalt i mikroaktuatorer.

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Roger
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