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Review on miniaturised paraffin phase change actuators, valves, and pumps

Sam Ogden, Lena Klintberg, Greger Thornell, Klas Hjort, Roger Bodén

Uppsala university, Micro Systems Technology

Corresponding author: Sam Ogden, Box 534, 751 21 Uppsala, Sweden, +46(0)184717235, sam.ogden@angstrom.uu.se

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Abstract

During the last fifteen years, miniaturised paraffin actuation has evolved through the need of a simple actuation principle, still able to deliver large strokes and high actuation forces at small scales. This is achieved by the large and rather incompressible volume expansion associated with the solid-to-liquid phase transition of paraffin. The common approach has been to encapsulate the paraffin by a stiff surrounding that directs the volume expansion towards a flexible membrane, which deflects in a directed stroke. However, a number of alternative methods have also been used in the literature. The most common applications to this date have been switches, positioning actuators, and microfluidic valves and pumps. This review will treat the historical background, as well as the fundamentals in paraffin actuation, including material properties of paraffin. Besides reviewing the three major groups of paraffin actuator applications; actuators, valves, and pumps, the modelling done on paraffin actuation will be explored. Furthermore, a section focusing on fabrication of paraffin microactuators is also included. The review ends with conclusions and outlook of the field, identifying unexplored potential of paraffin actuation.

1 Introduction

The use of paraffin as an actuator material has enabled miniaturised actuators, valves, pumps, and electrical switches, all capable of delivering both large stroke and high force. So far, this has been demonstrated in a wide variety of applications. In the coming sections, examples from Braille cell arrays, a deep sea sampler, and various lab-on-a-chip systems will be treated in detail. Paraffin exhibits material properties suitable for integration as well as ease of control, and paraffin-based actuators will most certainly continue to enable new functions in, and applications for, miniaturised components and systems in the coming years.

The aim of this review is to provide its readers and the potential users of paraffin for actuation purposes with an overview of the subject, as well as a general guideline to the use of paraffin-related actuation and its potential applications, particularly in miniaturised components and systems. The work summarises the current research on miniaturised paraffin actuators, including actuation principles, material properties, modelling, fabrication, and current applications, and ends with conclusions and outlook. This section of the review aims to give the reader an introduction to paraffin actuation. Details and references are saved for the following sections.

A phase changing material (PCM) utilises the phase change, e.g., from solid to liquid and/or from liquid to gas, to act as, in this case, an actuator material, transforming thermal energy to mechanical work. Especially over the last ten years, paraffin is a PCM that has attracted significant interest in the field of microelectromechanical systems (MEMS). Paraffin-driven actuation utilises the volume change associated with the solid-to-liquid phase transition, but can also be used in combination with other actuation principles, e.g. to enable latching capabilities in actuators and microfluidic valves.

Although paraffin offers a few challenges, for instance gas absorption, and requires sealing and wetting precautions, it has several attractive properties, as chemical inertness and ease of activation, as well as being a rather inexpensive and readily available material. However, the most important property is the high energy density of the material. Clearly, a high energy density is imperative in order to retain a sufficient actuator stroke and force in miniaturized actuators. The

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energy density, E_d, for an actuation material is defined in Eq. 1 as the energy available for work (Krulevich et al. 1996)

$$E_d = \sigma\varepsilon \qquad\qquad (1)$$

where σ is the material stress and ε is the material strain. Figure 1 compares the energy density of actuation materials commonly used in miniaturised actuators. For repeatable actuation, paraffin PCMs, followed by shape memory alloys (SMA), have the highest energy density, owing to the large volume expansion (10-15%) combined with a high load-bearing capability due to the low compressibility.
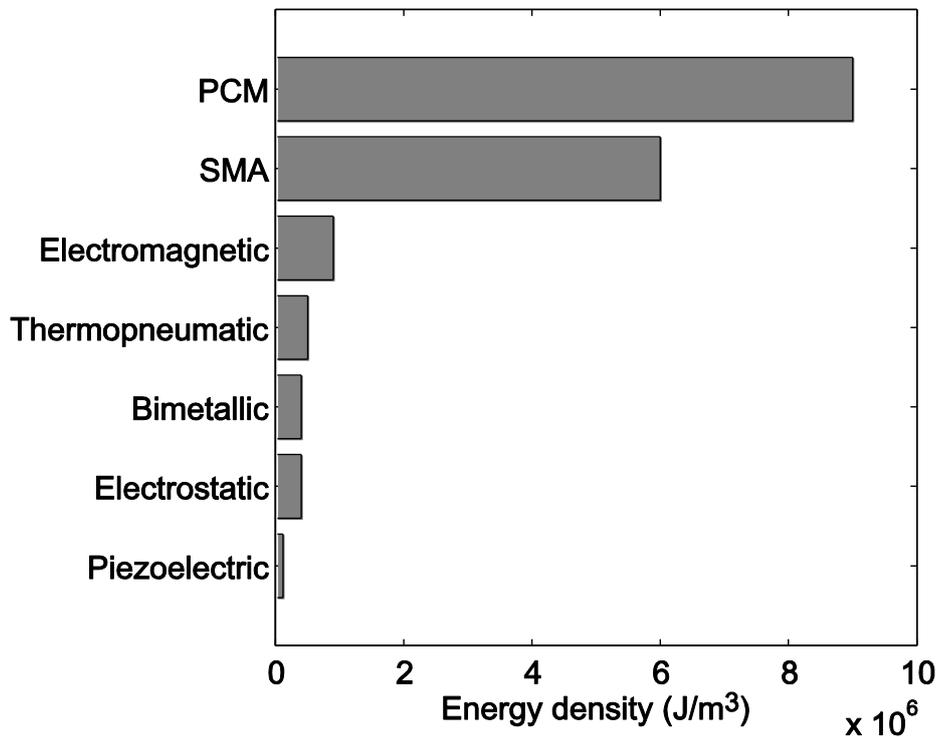

Figure 1. Energy densities of common actuation materials used in miniaturised actuators. Data from Krulevitch et al (1996) (thermopneumatic, bimetallic, and piezoelectric), Gilbertson and Busch (1996) (SMA, electromagnetic, and electrostatic), and Srinivasan and Spearing (2009) (PCM). The maximum value noted for PCM here, is from paraffin wax.

2 Historical background

At macroscale, waxes have been used for a very long time, serving purposes ranging from down-to-earth ones such as candle making, food preservation and cosmetics, to more exotic ones, like rocket propellant, forensics and neutron moderation.

The first use of the thermomechanical properties of paraffin wax dates back at least to 1929, when Georges Gaston Royer registered his patent application "Improvements in or relating to Thermostats" (Royer 1932). The invention is centred on using diluted ozokerite to allow for a freely adjustable switching temperature of a thermostat, but also clearly states that this is an alternative to "paraffin wax [which] has been commonly employed as a thermostatic material". In a patent application, entitled "Thermostat", from 1938, Sergius Vernet describes how a diaphragm with a piston is deflected by a material melting at a certain, pre-determined and assumingly critical, ambient temperature, underneath. The patent also describes how this movement can be used to control the flow of cooling water in cars (Vernet 1938). In this application the general term "morphologically transformable material" is used, and it was first in a later application (Vernet 1945), that wax, paraffin and alkanes were clearly mentioned. Between these two inventions, Vernet, now accompanied by two co-inventors, filed the patent application "Temperature Responsive Element" on a sort of composite containing, e.g., copper particles to increase the thermal conductivity (Vernet et al. 1941).

Following on these pioneering works, there were numerous patent applications describing a wide variety of wax-based transducers. Of these, the invention patented by John F. Sherwood (1957) should be noted. Primarily because it is a true, wax-based actuator since it was driven by an internal electrical heater, but also because it was claimed to be small and compact, as well as accurately controllable. This was likely the origin of the nowadays widely occurring wax motors, which, essentially, are electrically heated paraffin-driven piston actuators. These are typically found in household appliances, where they work as smoother and more forgiving alternatives to solenoids.

Paraffin entered aerospace on the Explorer 33 mission in 1966, where in-flight calibration of very sensitive magnetometers required mechanical flipping of

the instrument. As the conventional actuators were either too weak or limited in number of cycles, or contained too much of disturbing magnetic material, paraffin actuators were utilized to overcome these limitations (McCarthy 1968). With a few additions, such as a vapour-deposited thin-film heater circuit, an ordinary automotive thermostat was used. About a decade later, the same off-the-shelf component was used for a similar task on-board Voyager, with a further reduction in the amount of magnetic material present (Stange 1977).

In the late 80s, Maus Technologies offered a range of specially designed, yet similar, piston actuators dedicated for space use. Some exhibited actuation over just a couple of degrees centigrade, whereas others offered close to linear stroke vs. temperature over twenty degrees. Some were able to latch in order to, for instance, keep sunshades open without consuming power. They all had integrated heaters (Tibbitts 1988, 1991). The enterprise and technology were further developed under the flag of Starsys Research.

Paraffin wax actuators being no exception here, "micro" used together with "actuator", not only includes miniature devices, but also not so small devices offering high displacement resolution. This makes tracing the origin of the former ones somewhat challenging, at least if both MEMS-like and fine-mechanical components are included. However, and although their own experiments involved just a marginally miniaturized piston actuator, it appears as if Kabei et al. (1997), driven by tough requirements from endoscopic surgery, were the first to look at paraffin as an alternative to conventional but true microactuators, and acknowledge its remarkable energy density. This being as late as 1997, paraffin waxes must be said to have entered microactuator technology surprisingly late, especially considering their long history and quite broad usefulness, including that earned for their thermomechanical properties. At this time, actuation principles rarely used at macroscale, such as magnetostriction and piezoelectricity, had been more or less established in the field.

Properly cited, the work of Kabei et al. was followed by the realization of what must be considered the first microscopic, paraffin-based actuator, presented by Carlén et al. at the Transducers'99 conference (Carlén and Mastrangelo 1999). Employing lithography, thin film metallization and etching, diaphragm-covered patches of paraffin with a diameter of 300-800 µm and a height of 3-9 µm were

successfully manufactured and actuated to produce micrometer strokes. This marks the start of the era treated in this review.

3 Paraffin properties

The collective name paraffins denote alkanes, usually linear, with the universal formula C_nH_{2n+2}. Melting points ranging from approximately -125°C to 100°C (Freund et al. 1982), fig. 2, are achievable, depending on the chain lengths, with paraffins having an n equal to, or larger than 17, being solid at room temperature. The term paraffin wax refers to mixtures of alkanes of different chain lengths that are solid at room temperature, whereas the term paraffin oil is used when the melting point is below room temperature.
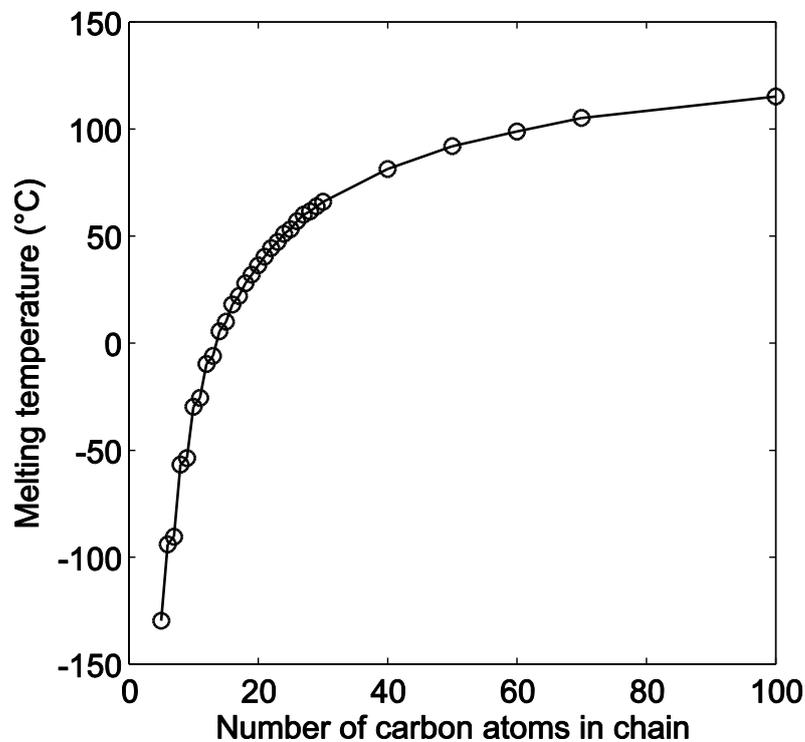

Figure 2. Melting point as a function of chain length for linear alkanes. Data from Freund et al. (1982).

There is a large volume change, typically 10-15%, coupled to the phase change from solid to liquid, and the expansion is retained to a large extent even at pressures up to 200 MPa (Zoller and Walsh 1995; Srivastava et. al. 1993), fig 3. Literature pressure-volume data (Zoller and Walsh 1995), gives a bulk modulus of about 1.3 GPa for liquid paraffin, which explains why paraffin actuators are so well suited for use in high stroke, high force actuators. As described by Lehto et al. (2007), when heating paraffin from room temperature to slightly above its

melting point, typically 5 to 15% of the total expansion comes from thermal expansion of the solid phase, 25-30% of the total expansion comes from solid-to-solid transitions, and about 60% to 70% comes from the melting. When further heated, the liquid paraffin continues to expand with approximately 0.1%/°C, as seen in fig. 3. In the same study, three different mixtures of two n-alkanes were evaluated, and the mixture content was found to affect the phase transition temperature as well as the width of the phase transition, effectively yielding a step-wise expansion.
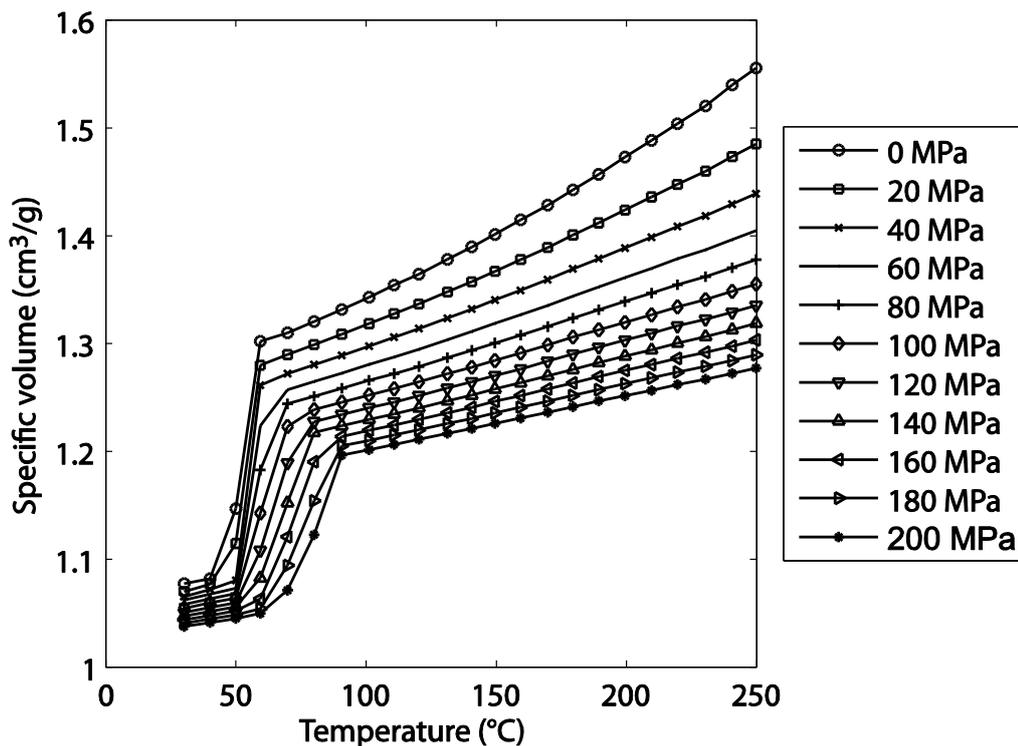

Figure 3. Specific volume for n-tetracosane ($C_{24}H_{50}$) as a function of temperature for pressures between 0 and 200 MPa. Data from Zoller and Walsh (1995).

The mechanical properties for a solid wax with a melting point of 53°C was studied at 25°C by Wang et al. (2006), giving a Young's modulus of 61.4 MPa, a tensile strength of 0.77 MPa, and an elongation at break of 12%. However, the mechanical properties of paraffin wax are very sensitive to temperature, indicated by a substantial decrease in both Young's modulus and tensile strength when heated beyond the solid state transition, but still below the melting point (Wang et al. 2007).

A large heat of fusion combined with small supercooling has led to extensive use of paraffin in energy storage applications (Mehling and Cabeza 2008; Sharma et al. 2009). The average heat of fusion is 170 J/g, but in many

paraffins, a broad-peak solid state phase transition is found near the melting point, giving a total heat of fusion of approximately 230 to 250 J/g (Mehling and Cabeza 2008). The solid-solid phase transition is fully reversible and consists of a change in the crystalline structure. The crystal structures involved in the phase transition depend on both the length of the alkane chains and if there is an even or odd number of carbon atoms in the chains (Freund et al. 1982). In both solid and liquid state, paraffin exhibits a specific heat of approximately 2 J/(gK), but the value depends on molecular weight, crystal structure, and temperature (Mehling and Cabeza 2008). Differential scanning calorimetry of paraffin visualizes solid state phase transitions below the melting point, fig. 4.
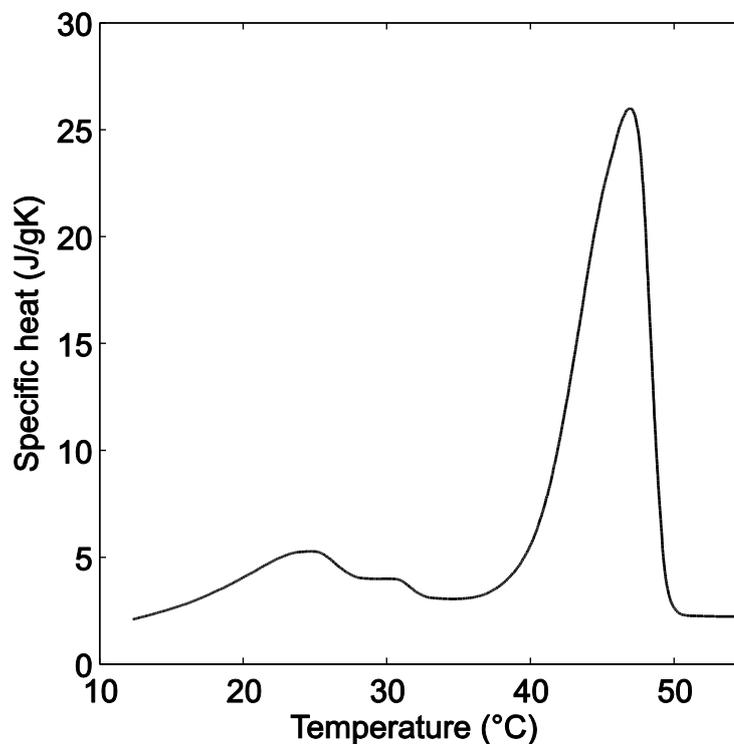
Figure 4. Differential scanning calorimetry measurement on paraffin reveals that there are solid state phase transitions (located at 25°C and 31°C) below the melting point at 46°C. Data from Malik et al. (2013)

The thermal conductivity of solid paraffin ranges from 0.2 to 0.4 W/mK (Mehling and Cabeza 2008). Generally, the thermal conductivity is lower for liquid paraffin, with a value of 0.15 W/mK given by Malik et al. (2013). However, this difference is more than compensated for by the convection. Both the need to apply high energy to melt the paraffin, as well as the low thermal conductivity will make it more favourable to miniaturise paraffin actuators, reducing the power consumption as well as decreasing the response time.

Chemically, paraffins are considered very stable compounds that do not react with most common chemical reagents, and make them suitable for long-life applications. High-energy radiation can however cause chain scissoring, resulting in smaller molecules (Charlesby 1954). Furthermore, paraffins can thermally degrade. For alkanes in general, 350°C can be used as a guideline (Freund et al. 1982), whereas paraffins decompose thermally at lower temperatures, about 210°C (Jaw et al. 2001) in ambient atmosphere. Paraffins are compatible with metals and ceramics, but can cause softening of some polymers (Mehling and Cabeza 2008). For example, poly(dimethylsiloxane) (PDMS), a common material in microfluidic applications, is permeable to hydrocarbons like paraffins (Lee et al. 2003), which can result in poor long-term stability of PDMS-based paraffin systems. This was later proved specifically for paraffin by Sharma et al. (2011a).

4 Actuator principle and design

A classification of miniaturized paraffin actuation is proposed, where five main design properties are identified: *material properties*, *activation* type, *actuation* method, means of *force transmission*, and type of *enclosure*. Table 1 groups paraffin microactuators found in literature according to this classification. The presented works are further divided in the table by sub-properties and type. Following this hierarchy for e.g. *actuation* yields: actuation – external latching – magnetic, leading us to the work of Oh et al. (2005), where the activation was accomplished by applying an external magnetic field to the paraffin, which was doped with magnetic particles. Since paraffin can be used both as the actuating material itself, and in combination with other actuator principles, this review distinguishes between *activation* of the paraffin material, i.e. merely melting it for, e.g., latching or unlatching a valve (Yang and Lin 2007, 2009), and *actuation*, i.e. when the activation of paraffin enables the actuator to deliver stroke or force.

The material properties can be modified by its chemical composition, i.e. by mixing paraffins of different chain lengths, to modify the thermal expansion curves (Lehto et al. 2007). By adding particles to paraffin, a composite material combining the thermal expansion of paraffin with electrical conductivity, e.g., for direct resistive heating (Goldschmidtböing et al. 2008; Sant et al. 2010), or magnetic susceptibility to enable magnetic actuation (Oh et al. 2005), as well as infrared light absorption for optical activation (Park et al. 2007) can be realized. Composites with other materials, such as polyimide (PI) (Klintberg at al. 2006) and PDMS (Dubois et al. 2006) have also been realized for additional functionality as well as to simplify device fabrication.

The most common approach to activation is through the use of resistive heaters, either integrated or positioned outside the actuator, although external activation has also been achieved through laser heating, assisted by absorbing particles in the paraffin (Park et al. 2007). For some applications, e.g. thermal switches, the activation takes place passively, governed by the surrounding temperature.

Actuation is normally accomplished by the paraffin itself, through its thermal expansion upon melting, although activation of the paraffin has been used in combination with other actuation methods for latching purposes. This is achieved by first activating the paraffin, which is then moved to a new position by

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external actuation, and finally solidifying it, latching the device in a new position. The external actuation has been made by pneumatics; e.g. by an external gas pump (Pal et al. 2004; Yang and Lin 2007, 2009), hydraulics; e.g. by the liquid flow in a channel (Liu et al. 2004a), by centrifugal forces (Park et al. 2007), and by an external magnet assisted by magnetic particles in the paraffin (Oh et al. 2005). Latching has also been achieved with paraffin actuation alone (Ogden et al. 2010; Jonsson et al. 2012). This can be achieved by controlling the solidification spatially, locking part of the paraffin body in a deflected position before the rest of the paraffin solidifies. It can also be made by using a low-melting-point alloy that is melted, actuated by paraffin, and finally solidified in its new position (Ogden et al. 2012). In both cases, the low thermal conductivity of paraffin is an advantage, allowing a sharp thermal gradient over short distances. Latching has also been performed by pairing paraffin actuators with silicon cantilevers locking a RF switch in different positions (Choi et al. 2009).

Force transmission has been achieved by using various agents: membranes (e.g. Selvaganapathy et al. 2003; Svensson et al. 2010; Feng et al. 2011), composites (Klintberg et al. 2002a), and pistons (Kabei et al. 1997; Bodén et al. 2006). In microvalves and dispensers, the force transmission has also been performed without an agent, i.e. by direct contact between the paraffin and a working fluid (Liu et al. 2004a, 2004b; Pal et al. 2004; Oh et al. 2005; Yousef et al. 2005; Park et al. 2007; Bodén et al. 2008b; Abi-Samra et al. 2011; Baek et al. 2013). Al-Faqheri et al. (2013) used air as a force transmission agent, and used the paraffin to valve venting holes.

The enclosure refers to the surrounding of the paraffin body. Often, the paraffin is encapsulated by both a rigid structure and the force transmitting agent, e.g. a flexible membrane. However, as previously mentioned, paraffin has also been used as solid plugs that can move freely within microfluidic channels when melted, and then either be flushed out or latched at new positions when solidified.

Table 1. Classification of miniaturised paraffin actuation found in literature.

Design Property	Sub-property	Type	References
Material properties	*Chemical Additives*	Paraffin mixtures	Lehto 2007
		Magnetic particles	Oh 2005
		Electrically conductive particles	Goldschmidtböing 2008; Sant 2010
		Optically absorbing particles	Park 2007
	Composites	Elastomeric	Dubois 2006
		Polymeric	Klintberg 2002a
Activation	*Active*	Internal resistive heating	e.g. Carlén 2002a; Lee 2005, 2007a; Bodén 2006b, 2008a
		External resistive heating	Klintberg 2003b
		Optical	Park 2007; Abi-Samra 2011
		Inductive	Baek 2013
		Forced convection	Al-Faqheri 2013
	Passive	Ambient heating	Klintberg 2002b
Actuation	*Active*	Paraffin volume expansion	e.g. Lehto 2008a; Sharma 2011a; Boustheen 2011
	External latching	Pneumatic	Pal 2004; Yang 2007, 2009
		Magnetic	Oh et al. 2005
		Hydraulic	Liu 2004a
		Centrifugal	Park 2007
	Internal latching (PCM)	Directional solidification	Ogden 2010; Jonsson 2012
		Low melting point alloy	Ogden 2012
		Mechanical latching structure	Choi 2009
Force transmission	*Direct*	Direct acting	Liu 2004a, 2004b; Pal 2004; Yousef 2005; Park 2007; Bodén 2008b;
	Agent	Membrane	e.g Selvaganapathy 2003; Svensson 2010; Feng 2011
		Piston	Kabei 1997; Bodén 2006a
		Bi-morph	Klintberg 2002a
		Low melting point alloy	Ogden 2012
		Composite	Klintberg 2002a
Enclosure	*Open*	Direct acting	Liu 2004a, 2004b; Pal 2004; Park 2007
	Encapsulated	Polymer	Klintberg 2002a, 2003b; Liu 2004a, 2004b; Bodén 2005, 2006b, 2008b; Park 2007; Yang 2007, 2009; Yoo 2007; Lehto 2008a, 2008b; Sant 2010; Feng 2011; Boustheen 2011; Abi-Samra 2011; Al-Faqheri 2013; Baek 2013
		Metal	Kobayashi 2004; Bodén 2008; Goldschmidtboing 2008; Ogden 2010, 2011; Svensson 2010; Sharma 2011b; Jonsson 2012

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Silicon/glass	Carlén 2002a, 2002b; Klintberg 2002b, 2003a; Selvaganapathy 2003; Pal 2004; Lee 2005, 2007a, 2007b; Grönland 2007; Choi 2009

5 Modelling

Lately, with the growing number of available software, modelling has increasingly been used as an aid in designing and evaluating components and systems. Modelling of paraffin devices is no exception. However, modelling paraffin requires the latent heat to be accounted for in the simulations. As the specific heat of paraffin is non-linear, and the substance generally undergoes multiple phase changes, the need for experimental data is necessary to build a truthful model. Furthermore, the physical behaviour of the material when changing from solid to liquid state is complicated to model, since several material parameters, e.g., density and viscosity, drastically change during the solid-to-liquid phase transition. Furthermore, the mechanical properties of paraffin change substantially during solid-to-solid phase transitions. Altogether, this makes modelling of phase-changing paraffin challenging, and the number of publications on the topic is still fairly low.

Kong et al. (2009) used modelling to study the volumetric change upon melting of hexadecane, which was modelled as a solid, introducing an effective conductivity accounting for the natural convection during the melting process. The simulations were verified successfully using a dedicated experimental device, comprising a cylindrical poly(methylmethacrylate) (PMMA) container filled with the PCM, submerged in a larger water-filled container with temperature control and readout. They studied the phase change at time rates in the order of minutes, assuming that the paraffin was close to thermal equilibrium during the experiments.

To evaluate PCMs as energy storage materials in buildings, Gowreesunker et al. (2012) used the Ansys flow simulation tool fluent to model phase change processes where conduction dominates the thermal transport, by introducing a specific heat that was different depending on if the material was cooled or heated. This was realized by incorporating a user defined function for the specific heat. The experimental validation was conducted in an environmental chamber with time frames in the order of hours. Further, the model was evaluated by using both the user defined function and the default function in the software to model

dynamic temperatures in a wall lined with a PCM, finding a substantial difference in the temperature response between the two methods.

The first modelling study conducted on a paraffin microactuator was presented by Lee and Lucyszyn (2007b) with the purpose of creating a design-aiding tool. It focused on thermal properties, and limited the thermal transfer to conduction only. Furthermore, the model was simplified by assuming that the thermal properties were constant in both the solid and liquid phases. Both analytical and finite element method (FEM) modelling was used to track the melting front inside a paraffin microactuator. In another study (Lee and Lucyszyn 2007a), they used the FEM to model the temperature and an analytical method to calculate the pressure within a paraffin container. The study was conducted using the theory of large deflections in a circular plate, clamped along its rim. In the study, experimentally obtained values were used to couple the actuation pressure present within the paraffin chamber to the deflection observed.

Kratz et al. (2007) used a lumped thermal model in Simulink to evaluate the thermal response of a heat switch and heat sink, both using paraffin as the active material. The study focused on scaling analyses for various geometrical parameters, as well as different thermal scenarios, and as a result mapped the boundaries wherein the thermal management unit studied was useful.

Bodén et al. (2008a) investigated the performance of a physical paraffin microactuator used in a micropump by modelling the paraffin as a thermally expanding solid. Good agreement was found between experimental and numerical results at low driving frequencies, whereas larger deviations were reported at higher frequencies. However, these deviations were a result of valve leakage, which was not accounted for in the model.

In an attempt to model the true behaviour of paraffin, Malik et al. (2013) designed a model that treated paraffin as a liquid throughout all phases, but with its viscosity varying with temperature. By this, convective heat transfer could be used in the model, and localized stresses and strains could be eliminated in the paraffin as if it was a hydraulic agent. Figure 5 shows modelled temperature and paraffin density inside the paraffin microactuator evaluated at different times.
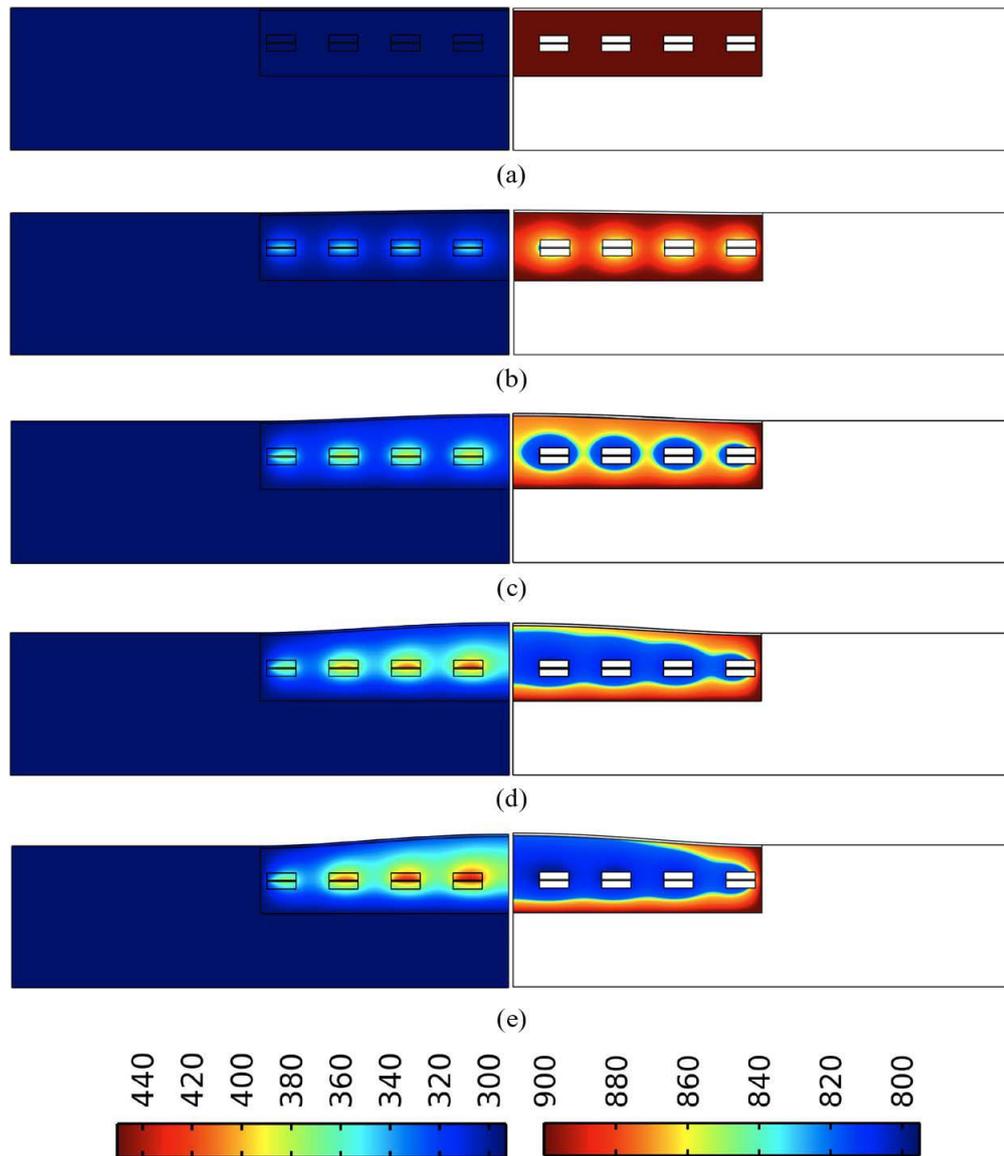
Figure 5. Modelled temperature (left) and paraffin density (right) distribution from Malik et al. (2013) at (a) $t = 0$ s (b) $t = 0.5$ s (c) $t = 0.75$ s (d) $t = 1$ s (e) $t = 2$ s during actuation of a paraffin microactuator. The scale bars show temperature in K (left), and density in kgm^{-3} (right). The small rectangles inside the paraffin cavity represent the heating elements. Reprinted with permission from IEEE.

Generally, due to a simpler approach, paraffin has been modelled as a thermally expanding solid, as only solid mechanics and thermal properties need to be addressed. However, although these simplified models are easier to create, these have to be tuned to the specific geometry used, especially thermal properties due to the lack of natural convection in the models. For instance, Bodén et al. (2008a) used an effective thermal conductivity for the liquid state about 30 times higher than the true value to compensate for this. By modelling the paraffin as a liquid in both states, this is not needed. Furthermore, when creating more

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advanced models, the interaction between, e.g., a membrane and a valve seat needs to be addressed. This behaviour becomes more truthful in a fluid model, since a liquid can conform to shape changes, and thus equalize localized loads, whereas a solid cannot. Another argument for using a fluid model is that solid paraffin behaves in a viscoelastic manner, i.e., yields with time when subjected to a static load (Ogden et al. 2010).

6 Fabrication

6.1 Paraffin deposition

Paraffin deposition is one of the main fabrication issues that need to be addressed. Depending on the fabrication scheme, the paraffin can be deposited in its solid, liquid, or gaseous state. If solid or liquid deposition is chosen, the paraffin needs to be outgassed prior to deposition in order to eliminate dissolved gas in the paraffin. Solid filling of paraffin was conducted by Baek et al. (2013) and Yousef et. al (2005), where pre-shaped slabs of paraffin were manually placed in a microfluidic channel to function as valves or placed at the bottom of a fluidic reservoir respectively. This approach is simple, but fails to seal against high pressures, since it is very difficult to perfectly match the channel size and geometry with a solid. There have been several examples of liquid filling, treated in detail below. The main difficulty associated with liquid filling of paraffin is that, due to the volumetric expansion of paraffin, the designated cavity needs to be overfilled to accommodate this volumetric reduction upon solidification. If high actuation pressures are required, a complete filling without gaseous inclusions is crucial, as a high actuation pressure relies on a low compressibility. Furthermore, the paraffin needs to be properly sealed to avoid leakage and corresponding loss of actuator stroke.

Primarily addressing the issue of gaseous inclusions, Klintberg et al. (2003a) used a setup consisting of a paraffin container with a movable piston, several valves, and a micrometer screw to evacuate gas and control the filling volume, fig. 6. The paraffin container was filled with degassed paraffin. Thereafter, the diaphragm pump was used to evacuate gas from the component. Finally, the pump valve (v3 in fig. 6) was closed, and the inlet valve (v2 in fig. 6) was opened to allow the paraffin to enter.
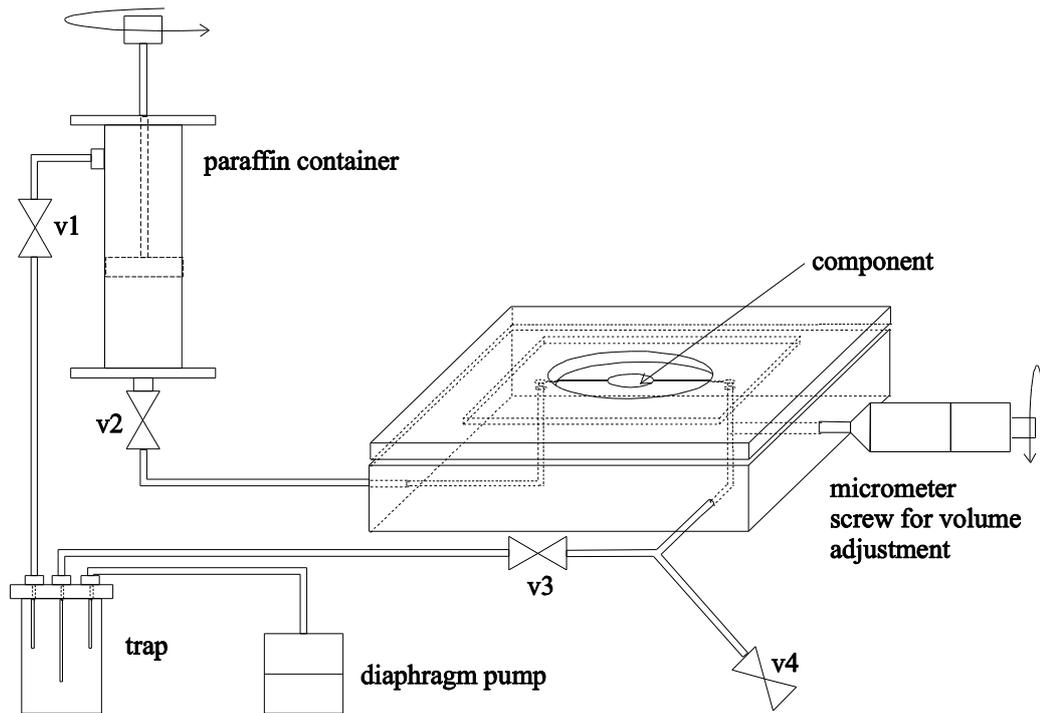
Figure 6. Paraffin-filling setup used by Klintberg et al. (2003a). Reprinted with permission from Elsevier.

An alternative method was developed by Carlén and Mastrangelo (2002a; 2002b) and used by Selvaganapathy et al. (2003), where paraffin was thermally evaporated onto a substrate, thus including the outgassing step into the deposition process. A mask was deposited and patterned onto the paraffin, and subsequently used to etch the paraffin. The actuator was sealed by coating it with a thin layer of Parylene C, which also functions as a membrane, fig. 7.
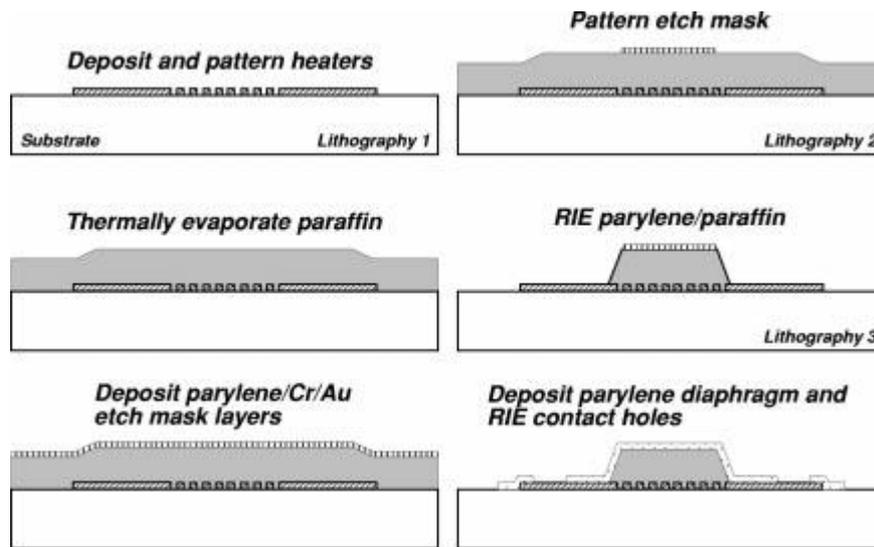
Figure 7. Paraffin deposition and actuator sealing technique developed by Carlén and Mastrangelo (2002a). Reprinted with permission from IEEE.

The examples mentioned above are the more exotic ways of depositing paraffin found in literature. The most common way has been, and still is, to cast it into open actuator cavities, leave it to solidify, preferably under vacuum, remove excess paraffin, and finally seal the device. Since paraffin contaminates most surfaces, the backside surface should be protected during paraffin casting to avoid compromising subsequent sealing of the device.

6.2 Materials

The most commonly used materials in microfabrication are silicon and glass. Paraffin-actuated devices being no exception, several devices have been manufactured in these materials, as can be seen in the materials section of table 1. Both glass and silicon exhibit high stiffness and yield strength, making them useful in high-force applications, where low deformations of the enclosure are critical. This will direct all the expansion from the actuator to the weaker force transmission agent. Furthermore, fusion or anodic bonding can be used to join different layers, creating a very strong sealing. Especially silicon exhibits a high thermal conductivity, enabling higher actuation frequencies, but also increases power consumption due to the large amount of heat being transported away during activation.

Another popular group of materials are polymers, especially PDMS for use in microfluidic systems (Yang and Lin 2007, 2009; Yoo et al. 2007; Feng and Chou 2011; Baek et al. 2013). However, even though strong bonds can be created, either between PDMS and glass or PDMS-PDMS, the fact that PDMS is an elastomer, makes it an unsuitable container for applications where high forces or pressures are present, either within the actuator cavity, or in a fluidic channel, as it will deform even at moderate pressures. Furthermore, PDMS is permeable to paraffin (Lee et al 2003; Sharma et al. 2011a), which also makes it unsuitable to contain paraffin under high actuation pressures or long actuation times. Besides PDMS, the use of polycarbonate (PC) is fairly frequent (Liu et al. 2004a, 2004b; Park et al. 2007; Boustheen et al. 2011) due to the multitude of tools available for fabrication (can be laser ablated, milled, molded, etc.), combined with its, by polymer standards, high stiffness and yield strength.

A third material class that has been used in paraffin microsystems is metals, mainly stainless steel (Kobayashi et al. 2004; Bodén et al. 2008; Ogden et al. 2010, 2011; Svensson et al. 2010; Sharma et al. 2011a, 2011b; Jonsson et al. 2012). Stainless steel offers both high stiffness and yield strength, but is difficult to bond directly. In all works using stainless steel, an intermediate layer of Parylene C was used as a bonding agent.

7 Applications

Commercial paraffin microactuators have been presented for applications like: flow control valves from NanoSpace AB (Grönland et al. 2007), as well as bi-stable valves and high power electrical switches from MultusMEMS AB (Lehto et al. 2008b). At the moment, NanoSpace AB has their paraffin valves in production, and the first ones have already been delivered.

In research, many paraffin-based microactuator devices have been demonstrated with proposed applications like positioning (Bodén et al. 2006a; Lehto et al. 2008b) or Braille displays (Lee and Lucyszyn 2005). Furthermore, the simplicity and non-toxic nature associated with paraffin microactuators has generated interest for single-use valve and dispensing applications, proposed in publications focused on lab-on-a-chip applications (Bodén et al. 2008b; Liu et al. 2004b; Park et al. 2007; Yousef et al. 2005). The high-pressure capability of paraffin-actuated valves has also enabled implementation of these in a deep-sea microfluidic sampler (Jonsson et al. 2012), fig. 8.

This section focuses on the main groups of miniaturized paraffin-based devices presented in the literature; actuators, valves, and pumps.
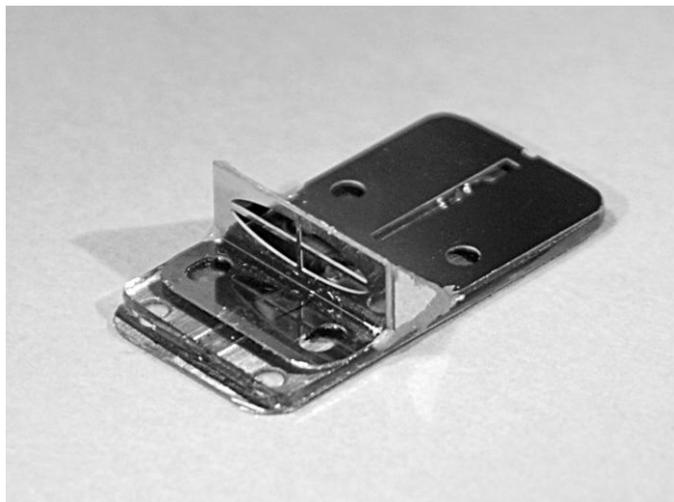

Figure 8. Photo of the deep-sea microfluidic sampler presented by Jonsson et al. (2012).

7.1 Actuators

Several miniaturized paraffin actuators have been presented in literature. Their properties and performance are summarised in table 2, which is limited to

include only actuators with a paraffin volume below 10 mm^3. The table summarises the reported performance as well as showing calculated figures of merit where applicable. As can be noted, the range of performance is very wide, with the amount of paraffin ranging from 4.4 to 0.001 mm^3, and with the wide variety of embodiments, to the range of performance, where maximum force and deflection ranges from 6 mN to 10 N and 2.7 μm to 17 mm, respectively, and power and actuation time ranges from 0.1 to 4.7 W and 3 ms to several minutes, respectively.

To be able to conduct a fair comparison between actuators of different types and sizes, the actuator work density W_d (work per unit volume), Eq. 2, and the energy efficiency η (work per unit input energy), Eq. 3, are normally used, (Krulevich et al. 1996)

$$W_d = \frac{F_{max} \, d_{max}}{2} \frac{1}{V} \tag{2}$$

$$\eta = \frac{F_{max} \, d_{max}}{2} \frac{1}{P_{in} t} \tag{3}$$

where F_{max} is the maximum force delivered, d_{max} is the maximum deflection reported, V is the volume of the actuation material, P_{in} is the input power, and t is the actuation time. These figures of merit normalize the performance of an actuator, enabling the comparison between actuators of different sizes, input powers, strokes, activation times, and forces. Unfortunately, reports on actuator performance are often incomplete, leading to difficulties in calculating these figures of merit.

The most common way to translate the paraffin expansion into a directed movement is through the use of a weak membrane-like member, although piston (Kabei et al. 1997; Bodén et al. 2006), fig. 9, as well as bimorph (Klintberg and Thornell 2002a) approaches have been reported.
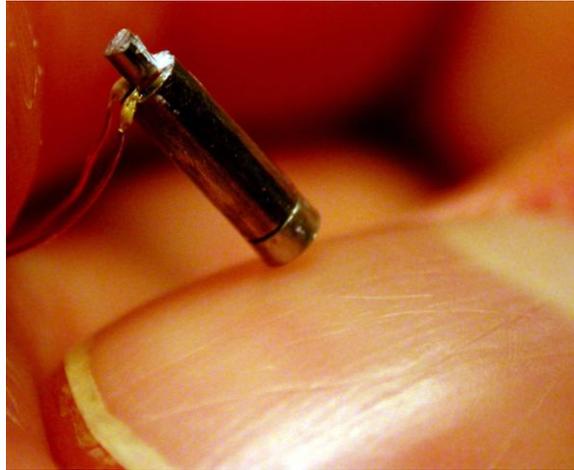
Figure 9. Piston actuator presented by Bodén et al. (2006)

The heat required to melt the paraffin is supplied either passively or actively. Passive heating by an increase in the ambient temperature, has been utilized in a heat switch for satellites (Klintberg et al. 2002b). However, the most common approach is active heating by various resistive heater structures.

Due to the relatively high power consumption in active paraffin actuators, various latching approaches have been developed. A common approach among actuators in general is mechanical latching through cantilever beam structures. This has also been demonstrated for a paraffin actuator (Choi et al. 2009) for use as a RF switch. Another approach is to use the paraffin as both actuator and latching agent for mirror positioning (Lehto and Bodén 2008b) and for valve operation (Ogden et al. 2010; Jonsson et al. 2012). In yet another approach, paraffin is combined with a low-melting-temperature alloy as a latching agent (Ogden et al. 2012) for a valve actuator.

From available literature data, it can be concluded that the highest values for work density and energy efficiency are found in actuators where high forces are reported. However, as seen in Eqs. 2 and 3, this contribution can be negated if the high forces are achieved by increasing paraffin volume and/or power consumption. Using metal as structural material, correlates with high forces, table 2.

Table 2. Paraffin actuator properties and performance, * indicates calculated values. SS – stainless steel, Si – silicon, PI – polyimide, PC – polycarbonate, PDMS – polydimethylsiloxane, Ti – titanium, Cu – copper, PCB – printed circuit board.

Type	Material (structure, moving part)	Paraffin volume (mm³)	Power (W)	Max force (N)	Max deflection (µm)	Actuation time (s)	Work density 10^3 (J/m³)	Energy efficiency 10^{-6}	Reference
Membrane	Glass, parylene	0.001*	0.10	-	2.7	0.05			**Carlen 2002a**
Membrane	Si, parylene	0.001*	0.50	-	2.7	0.005			**Carlen 2002a**
Bimorph	PI and epoxy, N/A	4.4*	-	0.006	17000	few seconds	12		**Klintberg 2002a**
Membrane	Si, Si	-	0.62*	0.53	15	minutes			**Klintberg 2003a**
Membrane	PC, PC	2.5*	-	-	140	-			**Klintberg 2003b**
Membrane	Epoxy, PI	0.7	-	-	51	5			**Lehto 2004**
Membrane	Glass/Si, PDMS	4.3	0.6	0.1*	654	60	7.2	1.7	**Lee 2005, 2007a, 2007b**
Membrane	PC, PI	0.5*	0.5	-	-	-			**Svedberg 2006**
Piston	Ti, Ti	2.7	0.16	10	140	30	260	290	**Bodén 2006**
Composite	Glass/PI, PDMS	-	0.16	0.6*	160	40*		15	**Dubois 2006**
Membrane	Cu, Si	2.1	1.90	-	14	2.5			**Goldschmidt böing 2008**
Membrane	Epoxy, PI	2.0*	0.22*	0.5	90	16*	11	13	**Lehto 2008**
Membrane	Silicon, PDMS		0.53/ 0.48			12-13			**Choi 2009**
Membrane	PCB (epoxy), silicone	2.8	0.69	-	0.6	6			**Sant 2010**
Membrane	SS, viton	1.1*	1.1	1.5	100	3	66	45	**Sharma 2011a**
Membrane latchable	SS, PI	2.3*	2.8	10	43	1	93	150	**Ogden 2010**
Membrane latchable	SS, PI	1.7*	4.7	2.7*	26	3	45	11	**Ogden 2011**

Incomplete reports of the performance of miniaturized actuators lead to difficulties in comparing actuators and actuator principles with each other. This

poses a hurdle for selection, design, and consequently, the use of miniaturized actuators. For miniaturized paraffin-driven actuators, the authors suggest that the following performance values should always be reported: paraffin volume, maximum deflection, maximum force, as well as corresponding actuation time and power. Furthermore, since both the actuation time and power depend on the ambient temperature, this should also be stated. If these are properly reported, it would enable the use of standard figures of merit like energy density and energy efficiency.

Although not needed to calculate figures of merit, the corresponding deactivation times should also be reported, since these usually rely on passive cooling and can differ substantially from the activation times. For example, in (Sharma 2011a), at low activation power, the deactivation time was only a third of the activation time, whereas at higher power the deactivation time had increased by a factor 2.5 and was twice the corresponding activation time.

In conclusion, actuator designs show a very wide diversity, depending on the intended application, manufacturing methods, choice of paraffin, etc. This makes comparison between different actuators complicated, which further raises the need for use of standard figures of merit. The importance of the design can also be seen in the actuators' work density compared to the actuator material's energy density. The maximum work density shown in table 2 is still a factor 30,000 less than the energy density of paraffin shown in fig. 1. In this sense, the actuator design can be seen as the means or agent for transforming the theoretical energy density into practical work density.

7.2 Valves

In many microfluidic systems, valves are necessary to control flow rates, fluid supply and timing. Valves are generally divided into two main subgroups, active and passive. Active valves need external power supply to hold or change their non-equilibrium state, whereas passive valves use the internal energy of the system, usually from the flow itself, to switch between states. Both types can further be classified as normally open (NO) or normally closed (NC), depending on the valve's non-activated state, and latchable/bistable (Oh and Ahn 2005). At macroscale, needle valves and ball valves dominate among active valves, and check valves among passive. However, due to their inherent three-dimensionality,

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as well as assembly tolerances, these types are difficult to fabricate at the microscale. In addition, the increasing relative importance of friction at smaller sizes further complicates miniaturization of these types of valves. The most common valve types among microvalves are instead membrane type and plug type valves. Membrane type microvalves are actuated by pressurizing a thin flexible membrane or diaphragm, acting as valve head, causing it to deflect into contact with a valve seat (in the NO configuration) to close the flow path. Plug valves, instead introduce a plug of solid material into the flow stream to close the flow path. Following the terminology introduced in the *Actuator principle and design* section, the difference between the two lie within the *force transmission* aspect, where membrane valves are classified as agent – membrane, and plug-type valves are classified as direct - direct acting.

As various kinds of microvalves have been treated separately in more detail (Oh and Ahn 2005), this paper will focus on the paraffin-actuated valves only. Furthermore, although most micropumps require, and thus contain, microvalves to function properly, this section only includes the valves that are explicitly characterised as such.

The first paraffin-actuated microvalves were presented in the early 2000's by Carlén and Mastrangelo (2002b) and Selvaganapathy et al. (2003). Both these valves were fabricated with either glass or silicon as a substrate material, utilizing traditional microfabrication processes, and Parylene C as a membrane material. Carlén and Mastrangelo (2002b) used silicon and glass wafers as substrates, with the parylene membrane layer deposited using chemical vapour deposition (CVD). The flow channel was realized by electroplating and patterning nickel on top of a thin layer of sacrificial photoresist. The valve managed to close against an applied pressure of nitrogen gas up to 800 torr (107 kPa) at a power consumption of 150 mW.
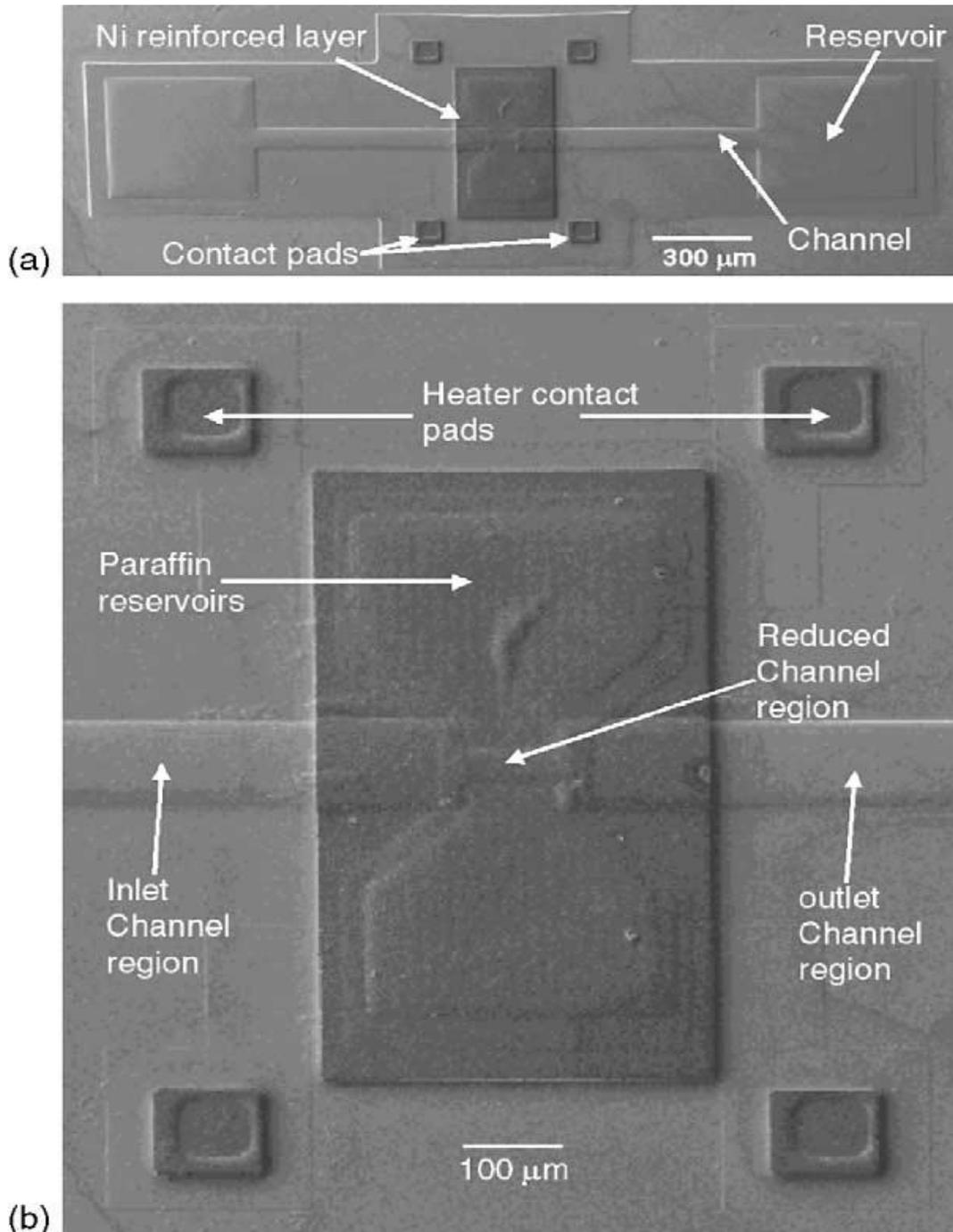
Figure 10. SEM photograph of the device presented by Selvaganapathy et al. (2003) showing (a), the valve system, and (b), a close-up of the valve. Reprinted with permission from Elsevier.

Selvaganapathy et al. (2003) presented a valve where the flow channel was comprised of a thin layer of parylene, which, at the site of the paraffin actuator, also functioned as the membrane, fig. 10. When melting the paraffin, the expansion caused the channel cross-sectional area to decrease, and ultimately close. The valve was evaluated at pressures ranging from 10 to 20 psi (34 to 138

kPa) with the power necessary to close the valve ranging from 30 to 210 mW within the same interval.

Besides the traditional microfabrication techniques in silicon and glass, several polymer-based paraffin microvalves have been presented, either fabricated in polycarbonate (PC) (Liu et al. 2004a; Park et al. 2007; Boustheen et al. 2011, Abi-Samra et al. 2011), PMMA (Al-Faqheri et al. 2013), or PDMS (Yoo et al. 2007; Feng and Chou 2011; Yang and Lin 2007, 2009; Baek et al. 2013).

Boustheen et al. (2011) presented a layered membrane microvalve fabricated by laser ablation of PC. The valve was a simple design of only three layers: the actuator layer and the fluidic layer, both fabricated in PC with a PDMS membrane sandwiched in between. The valve managed to withstand an applied pressure of 3 kPa at a power consumption of 25 mW. The authors also used water dyed red with rhodamine B to evaluate the dynamic characteristics of their valve. When the valve was in the open state, the dyed water was flowing over the valve, increasing the intensity of reflected red light from the valve. Upon closing the valve, a shift in color intensity towards green and blue could be observed. Recently, they evaluated the manufacturing and assembly concepts of the same valve design (Boustheen et al. 2012).

Yoo et al. (2007) presented valves constructed in PDMS, intended to seal the inlet and outlet of a thermopneumatic pump. The authors investigated the influence of the valve diameter and membrane thickness on the power needed to close the valve at an applied flow rate of 300 µL/min, but could find no clear dependence from either geometrical feature.

Lee et al. (2007a) presented a microvalve consisting of two silicon wafers, sandwiched between a PDMS membrane and a glass wafer comprising a patterned gold heater. The silicon wafers were joined using a glass frit powder to seal any gaps at the interfaces.

The first paraffin-actuated microvalve utilizing stainless steel as a fabrication material was presented by Kobayashi et al. (2004). This valve, created from laminated sheets of stainless steel and polyimide, joined by an intermediate layer of Parylene C, managed to close against a gas flow with less than 0.1 sccm leakage in the range of 0-100 kPa. Later, Sharma et al. (2011b) presented the strongest yet paraffin-actuated microvalve, also fabricated from sheets of stainless steel, capable of sealing against 20 MPa applied back-pressures of both water and

air. Notable though, is that this pressure was not the maximum pressure the valves could handle, but instead the pressure at which the fluidic connections failed.

Feng and Chou (2011) presented the first paraffin-actuated NC membrane microvalve, also constructed in PDMS, wherein the PDMS composition ratios (elastomer:curing agent) influence on the back pressure was also evaluated. The back pressure could be varied between 1 and 25 kPa by changing the composition ratio from 50 to 20.

Yang and Lin presented two varieties of a latchable valve principle (2007, 2009), where the valves had a paraffin compartment used for latching, wherein the paraffin was melted, and subsequently allowed to solidify under an applied pneumatic pressure to close the valve. To reopen the valve, the paraffin was melted and allowed to solidify without the applied pressure. This concept was further developed by Ogden et al. (2010) and Jonsson et al. (2012), who created a self-contained valve actuation principle by coupling three individually addressable paraffin cavities. The paraffin in these cavities was sequentially melted and solidified in specific orders to either open or close the valves. Although these valves demanded high input power during their latching cycles, the average power consumption over a latched period, 100 min and 19 h respectively, only amounted to 4.5 and 0.20 mW, respectively.

The first paraffin-actuated microvalve of plug type was presented by Liu et al. (2004a). The work focused on how to realize simple, plug-type microvalves in microchannels fabricated in polycarbonate (PC). Several varieties of this valve were presented: a single-use NC, a one-shot switching valve, fig. 11, and a NO variety that could be closed and then reopened before the valve was spent, all of them actuated by resistive heaters in combination with the pressure from a pneumatic pump or the fluid flow itself.
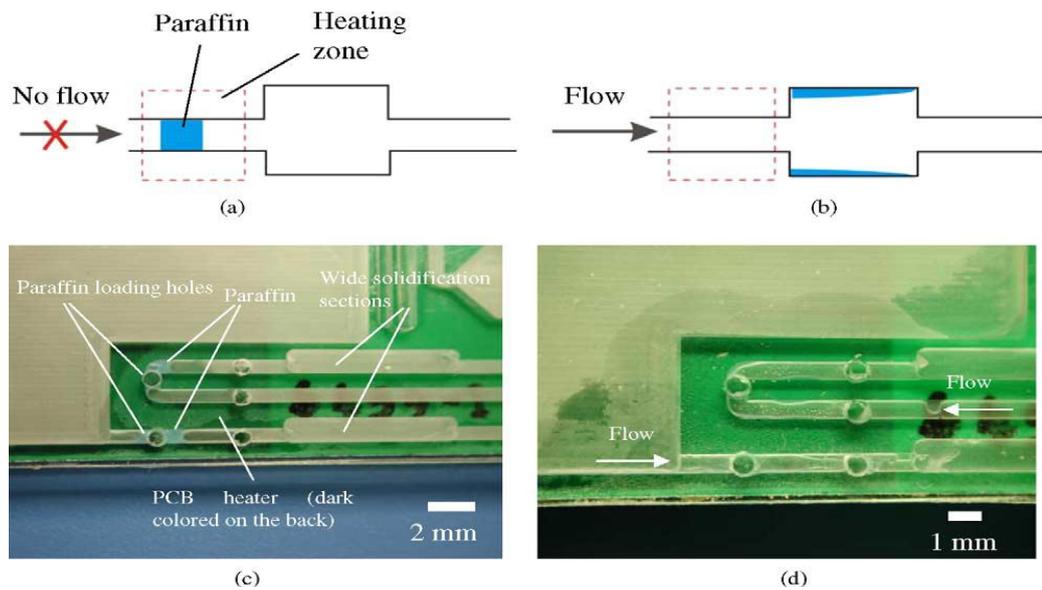
Figure 11. Single-use NC valve from Liu et al. (2004a), where (a) and (b) is schematics of the valve in its closed and open states respectively, (c) shows the paraffin plugs before actuation, and (d) shows the system after the valves have been opened. Reprinted with permission from Elsevier.

Pal et al. (2004) elaborated on the plug valve approach and introduced a microvalve with a moveable paraffin plug. Integrated heaters were used to control the state of the paraffin that was introduced into the flow path by applying a pneumatic pressure on liquid paraffin through a separate feed channel. The valve was reopened by creating an underpressure in this channel after the paraffin had been melted again.

Oh et al. (2005) further developed the plug valve by doping the paraffin with a ferrofluid, allowing magnetic actuation of the paraffin. With a Y-channel approach similar to that of Pal et al. (2004), a paraffin plug was both introduced and withdrawn from the flow path by activating different magnets.

A few years later, Park et al. (2007) presented a microvalve employing the same principle as Liu et al. (2004a), melting and solidifying paraffin within the fluidic channel to change the valve state. However, instead of using resistive heaters, the paraffin was doped with iron oxide nanoparticles to enable heating by laser. They presented both a NO and a NC variety of their valve, fabricated on PC by milling. The reported pressure capability of these valves were 403 and 125 kPa, respectively. They also evaluated the response time as a function of laser power and volume fraction nanoparticles.

Elaborating on the use of paraffin valving on microfluidic discs, Abi-Samra et al. (2011) and Al-Faqheri et al. (2013) both used paraffins with different melting points to be able to sequentially release liquid on the discs. Al-Faqheri also introduced an air force transmission, effectively separating the working fluid, both from possible paraffin contamination and from the heated zone during actuation. They used the term vacuum/compression valves, and used the paraffin to seal supply holes, either at the inlet (vacuum valve), or at the outlet, letting the decompression or compression of the air keep liquids at their designated reservoirs until valves were opened.

Baek et al. (2013) presented a microvalve, fabricated in PDMS, which used inductively heated metal discs, of either copper or nickel, to melt paraffin plugs in the flow path. Two valves on the same chip was reported, where the use of different discs at the respective valve sites enabled sequential opening of the two valves using the same magnetic field.

Table 3 summarizes the performance of the paraffin microvalves presented, and fig. 12 charts the valves based on response time and leak pressure.

In general, the valves fabricated on silicon and glass are the fastest, and the valves fabricated in stainless steel can handle the highest pressures. The superior speed found in the silicon and glass devices could be partly attributed to the higher thermal conductivity of the materials, especially silicon, but mostly to the fact that these materials allow for smaller devices through the traditional MEMS processing techniques, with the thickness being the most influential size parameter with respect to response time.

The *leak pressure* is a parameter of great interest, as it reveals the maximum leak-free operating pressure of the valve. However, this value can be misleading since different authors have different views on which flow is considered a leakage.

Power consumption is also of interest, especially for cordless applications, which usually have a limited energy supply. It is difficult to see any clear dependence between power consumption and the other reported parameters shown in table 3. This is probably due to the large size-range the valves are found in. However, since the size is seldom explicitly reported, it is difficult to take into account here.

Response time will limit the application in terms of switching speed. These three factors should always be reported from any valve characterization, and are available in most reports considered here. Besides these three, one additional parameter should be evaluated, the *maximum flow for an open valve*, which all but two (Carlén and Mastrangelo 2002b; Kobayashi et al. 2004) have overlooked, admittedly also the authors of this paper. Although this is a system parameter depending on many factors, e.g., connections, length of flow paths in the valve, etc., the main restricting factor in a well-balanced system should be the valves within.

Table 3. Summary of paraffin valves and their performance. SS-stainless steel, PDMS-poly(dimethylsiloxane), PC-polycarbonate, PMMA-polymethylmetacrylate

| Valve type	Valve state	Leak pressure (kPa)	Power consumption (W)	Response time (s)	Main structural material	Reference
Membrane	Active NO	107 (gas)	0.05-0.15	0.033	Silicon, glass	**1. Carlén 2002b**
Membrane	Active NO	138	0.03-0.210	0.015	Glass, parylene	**2. Selvaganapathy 2003**
Membrane	Active NO	3	0.025	7 (open) 9 (close)	PC	**3. Boustheen 2011**
Membrane	Active NO	N/A	0.3-0.35	1	PDMS	**4. Yoo 2007**
Membrane	Active NO	100 (gas)	N/A 12-16 V actuation	60 (open) 20 (close)	SS	**5. Kobayashi 2004**
Membrane	Active NO	N/A	N/A 15 V actuation	N/A	Silicon, glass	**6. Lee 2007a**
Membrane	Active NO	20,000 (gas, liquid)	0.4-0.6	0.2-0.3 (open) 0.2-0.6 (close)	SS	**7. Sharma 2011b**
Membrane	Active NC	25	N/A 3-6 V actuation	0.125 (open) 3.5-5 (close)	PDMS	**8. Feng 2011**
Membrane	Latchable NO	35 (latched)	N/A	100 (open) 60 (close)	PDMS	**9. Yang 2007**
Membrane	Latchable NO	60 (latched)	0.5	4-5	PDMS	**10. Yang 2009**
Membrane	Latchable NO	2,500 (latched)	0/2.8	7 (open) 1 (close)	SS	**11. Ogden 2010**
Membrane	Latchable NO	12,500 (latched)	0/4	4 (open) 1 (close)	SS	**12. Jonsson 2012**
Plug	Latchable NO or NC	280	0.2	20	PC	**13. Liu 2004a**
Plug	Latchable NO or NC	1,700	0/5	1	Silicon, glass	**14. Pal 2004**
Plug	Latchable NO or NC	345	N/A	N/A	Silicon, glass	**15. Oh 2005**
Plug	Active NO or NC	125 NO 403 NC	1.5	0.444 (close) 0.012 (open)	PC	**16. Park 2007**
Plug	NC	N/A	N/A	N/A	PC	**17. Abi-Samra 2011**
Plug	NC	N/A	N/A	480	PMMA	**18. Al-Faqheri 2013**
Plug	Active NC	107	N/A (110 µT magnetic field)	9	PDMS	**19. Baek 2013**

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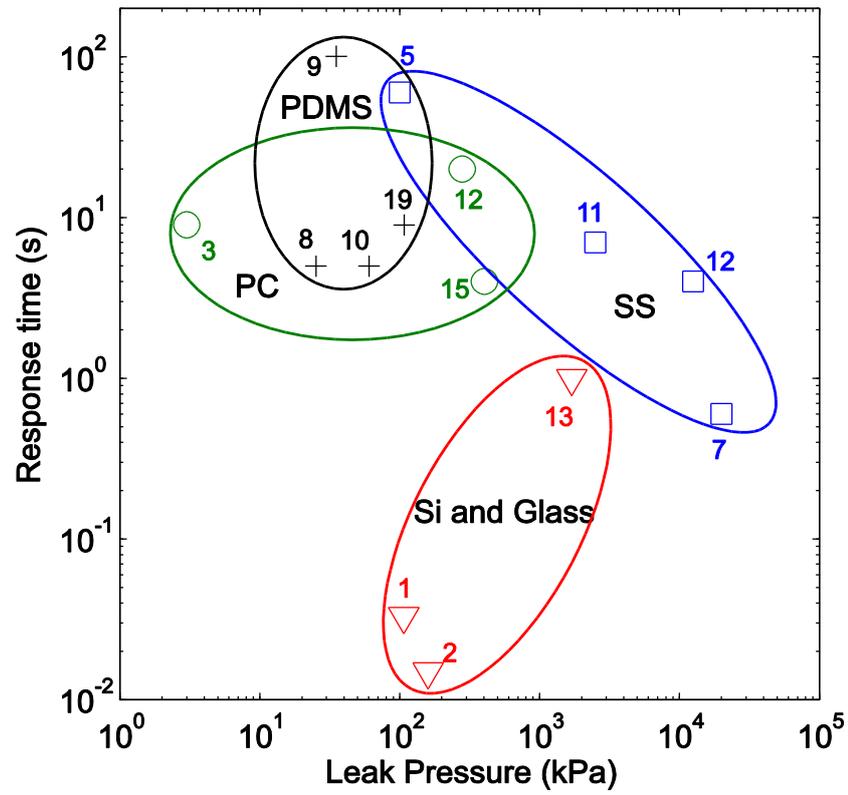
Figure 12. Grouping of valves by main structural material. The numbers refer to the works in Table 3.

7.3 Micropumps

Another interesting area of use for actuators in microfluidics is micropumps. Here, the actuator is used to displace fluid in a pump chamber, which, in combination with passive or active valves, or even without valves, can create a directional flow. At the highest level, pump classification is usually done by distinguishing displacement (mechanical) and dynamic (non-mechanical). Displacement pumps use various kinds of moving parts to displace the fluid, whereas dynamic pumps have no moving parts but instead typically rely on magnetic or electric fields in order to manipulate the fluid (Laser and Santiago 2004).

Traditional displacement pump principles at macroscale, using, e.g., rotating parts or moving pistons, generally suffer from reduced efficiency with decreasing pump size. This is primarily because of the increased surface-to-volume ratio in miniaturized systems, which increases the relative importance of friction between sliding parts. For pistons, difficulties arise due to imperfect sealings, even if there are examples where this has been resolved (De Volder et al. 2010). Another reason for the reduction in efficiency is manufacturing difficulties, especially fitting tolerances, as a micropump is typically smaller than a cubic centimetre. To overcome these issues, micropumps often use membranes to displace the fluid (Laser and Santiago 2004).

There are many actuation principles available for micropumps, evident from previous reviews (Laser and Santiago 2004; Iverson and Garimella 2008). Figure 13 illustrates the current status of the field in terms of achievable pressure and flow rate with respect to actuation principle. For very high pressures, in the order of megapascals, there are currently only two relevant types: electroosmotic flow (EOF) and paraffin-driven.

Electroosmotic flow is a non-mechanical pump principle that works by inducing and moving charged areas in the liquid. For EOF to function, the pumped liquid has to be polar or polarisable in order to establish the necessary electric double layer. Furthermore, the driving voltage required for high pressures is very high, often in the kilovolt range (Squires and Quake 2005). In addition, since gases cannot be pumped, such a pump cannot fill itself with liquid from an initially empty state (self-priming). Paraffin-driven micropumps compare well

with EOF in terms of achievable pressure, although the thermal actuation limits the pumping frequency and thus the flow rate.
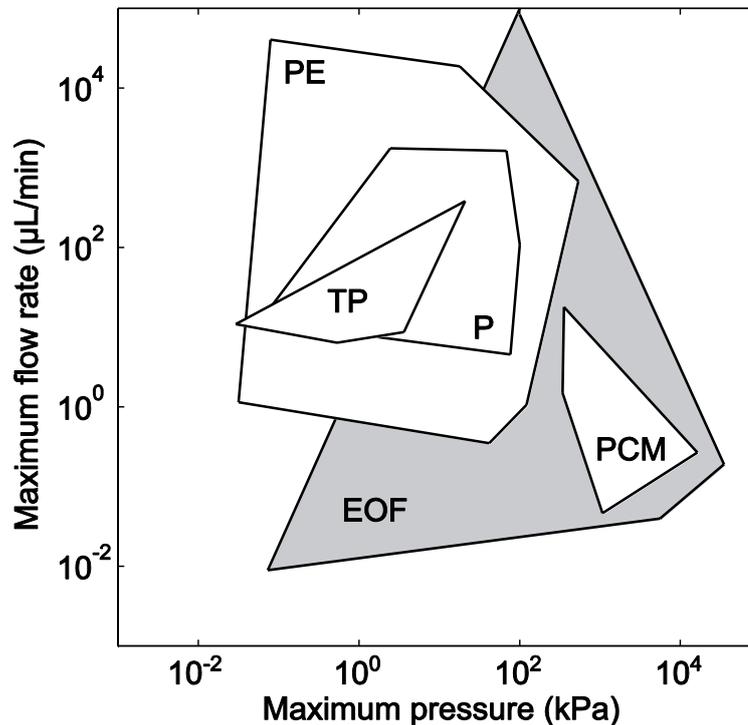

Figure 13. Comparison of the main types of micropumps presented in the literature regarding maximum flow rate and maximum pressure (Bodén et al. 2006, 2008a, 2008b, 2008c; Svensson et al. 2010; Laser and Santiago 2004; Iverson and Garimella 2008). White – displacement, grey – dynamic, EOF – electroosmotic flow, P – pneumatic, PCM – phase change material: paraffin, PE – piezoelectric, and TP – thermopneumatic.

The first paraffin-actuated reciprocating displacement micropump was presented in 2005 (Bodén et al. 2005). Further developed (Bodén et al. 2006), this pump was epoxy-based and exhibited a pressure capability near the megapascal region. For even higher pressures, currently up to 13 MPa, stainless steel based micropumps have been developed (Bodén et al. 2008, Svensson et al. 2010), where thermal simulations (Bodén et al. 2008a) and in-situ thermal measurements (Svensson et al. 2010) were also included in the studies.

Aperiodic displacement micropumps driven by paraffin emerged during the same time period. These pumps exert a finite volume of working fluid, e.g. similar to the macroscale syringe pump, and can either be for single use or refillable for multiple dispensing actions. Early preliminary research on aperiodic paraffin micropumps includes a liquid dispenser containing a microneedle array (Yousef et al. 2005), where a fluidic reservoir is located between the paraffin

actuator and microneedle array. The reservoir is first filled by letting the pre-heated actuator cool with a drop of water on top of the array. When the actuator is re-heated, the water will be dispensed through the needles. The first aperiodic micropump manufactured in silicon and glass was a micropipette presented by Lee and Lucyszyn (2007a, 2007b). Four separately addressed paraffin microactuators were integrated in a glass embodiment, enabling variable dispensing of four discrete volumes up to 6.74 μL. Later, a disposable lab-on-a-chip injector with simple actuation was presented (Bodén et al. 2008b), fig. 14. The injector consisted of three separately addressed paraffin actuators, each coupled to its own fluidic reservoir, enabling sequential dispensing of three different pre-filled fluids.
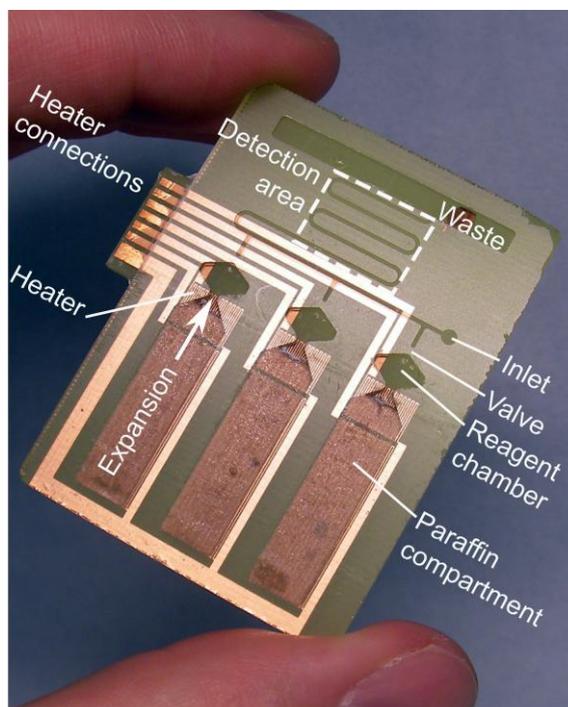

Figure 14. Aperiodic Lab-on-a-chip dispenser system presented by Bodén et al. (2008b), with three separately addressable paraffin cavities. When the paraffin melts, it expands and ejects a reagent from its corresponding chamber.

Addressing the need to dispense finite volumes against elevated back-pressures, a stainless steel-based high-pressure micropump was used as both a reciprocating and an aperiodic pump, depending on the driving scheme. This pump showed no pressure influence on the flow characteristics in injection mode within the measured interval (0-2.3 MPa) (Bodén 2008c).

The characteristics of the paraffin micropumps presented here can be seen in Table 4. Comparison of the pumps is done using the pump efficiency factor, E, calculated according to

$$E = \frac{Q_{max} \cdot p_{max}}{2P_{in}} \qquad (4)$$

where Q_{max} is the maximum flow rate at zero back-pressure, p_{max} is the maximum pressure resulting in zero flow rate, and P_{in} is the input power. The pump efficiency for these paraffin micropumps is in the order of 10^{-6}–10^{-4}, table 4. For comparison with other relatively strong micropumps driven by other principles, the order of magnitude of the pump efficiency can be seen in fig. 15.
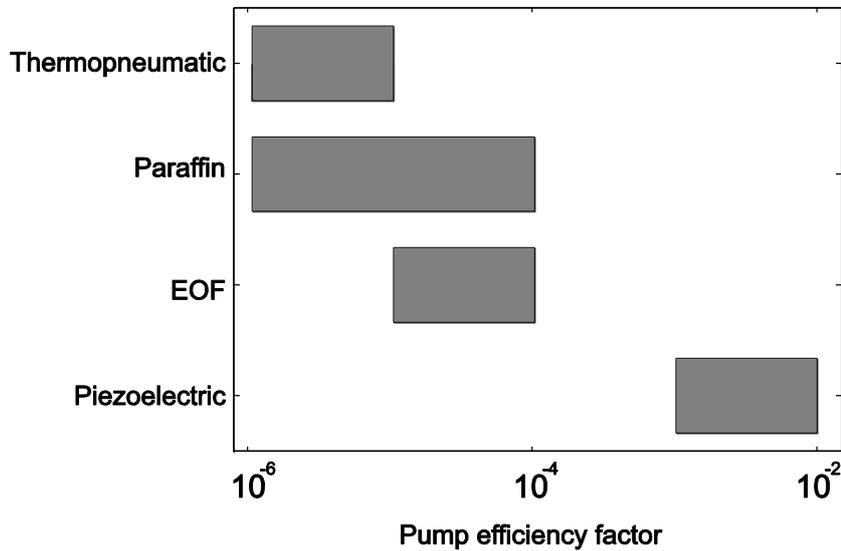

Figure 15. Comparison of pump efficiencies for different actuation principles from (Nguyen and Wereley 2006; Laser and Santiago 2004; Iverson and Garimella 2008).

As seen, paraffin-driven micropumps compare well with electroosmotic pumps, also having high-pressure capabilities. However, they cannot compete with the efficiency of piezoelectric micropumps due to their very high achievable flow rates, and relatively low power consumption, which, even at their moderate pressures, yields them a high pump efficiency factor.

Table 4. Comparison of paraffin micropumps. Q_{max} – maximum flow rate, p_{max} – maximum pressure, P_{in} – input power and E – pump efficiency.(SS-Stainless steel)

Main material	Mode	Q_{max} (μL/min)	p_{max} (MPa)	P_{in} (W)	E (μW/W)	Reference
Epoxy	Reciprocating	0.08	0.9	0.4	2	**Bodén 2005, 2006**
SS	Reciprocating	1	5	1.1	38	**Bodén 2008a**
SS	Reciprocating	0.4	13	1.3	33	**Svensson 2010**
SS	Reciprocating	2.4	2.3	1.1	40	**Bodén 2008c**
	Aperiodic	1.4	2.3	1.1	13	
Epoxy/PDMS	Aperiodic	-	-	-	-	**Yousef 2005**
Silicon/glass	Aperiodic	40.4	-	-	-	**Lee 2007a, 2007b**
Epoxy	Aperiodic	240	0.3	1.6	358	**Bodén 2008b**

8 Conclusions and Outlook

Paraffin-driven microvalves and micropumps can be enabling components for true micro total analysis systems (µTAS) and lab-on-a-chip (LOC) technology. Firstly, the low cost of paraffin, as well as the simple drive and control make paraffin actuators suitable for integration in portable and disposable systems. Secondly, the high-pressure capability, due to the low compressibility of the expanding paraffin, enables operations on chip, e.g. filter steps for sample preparation and pressure driven separations that are normally done off-chip. Most works focus on either the simplicity offered or the high energy density associated with paraffin actuation.

Paraffin phase change actuation comes to its best use in applications where its large hydraulic force and volume expansion are needed in repeated sequences, like in multi-cycle diaphragm valves, dispensers, and pumps. Its main limitations are fairly low energy efficiency and slow cooling due to its low thermal conductivity. When comparing with macro-scale paraffin actuators, niche applications where the paraffin actuator has been highly competitive are thermostats and thermal switches. Most works, especially early ones, are focused on fabrication technology and single-actuator devices. Besides actuators, microfluidic valves are the most common applications, which has also been the main focus in the few systems presented until now. The integration of paraffin microactuation into systems, especially for lab-on-a-chip applications, has increased lately, and is likely to be the main focus of the field in the coming years. Further evidence for the field's evolvement is found in that paraffin-actuated microdevices have reached the market as fully commercialised products.

When looking in the rear-view mirror, an interesting notion emerges: while the microsystem community in general has been moving towards smaller and smaller components and devices, and ultimately, evolving into nanotechnology, paraffin actuators have actually evolved in the opposite direction. The first published papers used traditional MEMS processing techniques and materials, whereas later research has shifted towards back-end manufacturing processes like micromilling, laser ablation, and molding. With this shift in manufacturing techniques, the minimum size and resolution of components have been sacrificed for a simpler manufacturing process.

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Future research may include improved paraffin filling schemes as well as enhancing actuator fabrication processes, aiming towards batch fabrication.

Another area of research is to further improve the pressure capability of devices in order to reach the limit of the paraffin itself, which is orders of magnitudes higher than what current systems can handle. Higher pressures or forces will increase the energy efficiency and work density of paraffin devices. In order to reach these pressures, research on new encapsulation and sealing techniques is required. The shift towards higher pressures is especially prominent among micropumps.

Two final aspects will conclude this outlook: First, as mentioned in the historical background, the two major applications for paraffin actuators at macroscale have been wax motors and thermostats. However, at microscale only the miniaturized equivalents of the wax motors have been thoroughly pursued. There could be good reasons in using passive paraffin actuation for miniaturized thermostats, either in blenders or in single flow regulator valves. Second, although the first miniaturized paraffin actuators were small, the following actuators, especially ones in microfluidic applications, have been fairly large. However, with the increased interest in nanofluidics there are reasons to revisit the techniques for highly miniaturized actuators that Carlén and Mastrangelo introduced into more advanced high pressure nanofluidic systems, with even shorter transport paths and response times.

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