Department of Precision and Microsystems Engineering

Conceptual development of a catalytic expansion actuator for a resonating-body flapping-wing micro air vehicle

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Abstract

In this project a start has been made in the conceptual and practical development of a hydrogen peroxide catalytic micro expansion engine. The liquid fuel convertor is designed specifically to mechanically actuate a resonant body flapping wing micro air vehicle of approximately 4 gram.

The actuator functionality is devided in several sub functions which were analysed using knowledge of scaling, boundary conditions and previous research. This resulted in a functional design description. (Chapter 2, 3)

The design description was used to make a working concept, critical components and functionalities were defined. The components to provide fuel delivery and reaction were selected for further development. (Chapter 4)

Capillary action is a very interesting phenomenon to provide fuel transport and accumulation at the reaction site. It can repeatedly provide a fuel volume with a sufficiently high flow rate. The size of channels have to be in the order of 1mm, surface tension can also provide a back pressure. Uncertainties are encountered when integrating the system with batched reaction. The amount of fuel transferred/reacted is a complex function of time, shapes and material properties. (Chapter 5)

Production of manganese oxide material was performed on aluminium plates to find a light and practical substrate for the catalyst. Fabrication parameters were varied to optimize the robustness and activity of the layer. (Chapter 6)

A design is made and tested of a simple prototype for the actuator consisting of a fuel delivery system and a timed catalytic reaction in a combined reaction-expansion chamber. Temporary components are used to perform the functions of fuel storage, expansion, exhaust and suspending. These components will be designed in a later stage. (Chapter 7)
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Chapter 1

Introduction

1.1 Atalanta

The aim of the Atalanta project is to develop a mechatronic butterfly which is capable of flying around in an environment such as a home, office, boat or car. The Atalanta project must be self-contained with respect to energy management, localization and navigation. This dream has challenges in many areas, such as low-energy consumption, advanced power supply, micro actuators, wireless communication and swarm behaviour, sensors for in-flight navigation and localization. The primary goal of the project is not realizing a final product, but obtaining the knowledge created in the research and prototyping phase [14].

The intended dimensions are a maximum span of 100 mm and a maximum vehicle mass of 4 g. The targeted dimensions are feasible by making use of conventional technologies such as gears, links and electric motors. However, these dimensions are also the starting point for other technologies, such as: linear actuators and compliant mechanisms, which are more promising when scaling down the butterfly in a later stage of the project.

1.2 Flapping Wing Mechanism

The project started with C. Bolsman who investigated flapping wing actuation by using resonant compliant mechanisms during his PhD. Nature shows beautiful examples of small flying objects that are able to hover and fly slowly. Insects and small birds achieve this with smart compliant wings that are driven by the motion of their resonating bodies. The resonance is exploited to reduce the energy required for flying.

1.2.1 Working principle

Bolsman’s final design, shown in Figure 1.2a, is the basis for the Atalanta Micro Air Vehicle (MAV). It consists of four wings that are connected to two flexible rings. The motion of the rings is amplified and transferred to the wings by linkages. When the structure is in resonance, kinetic and potential energy is exchanged from the rings to the wings and vice versa. Inspired by insects, the resonant state of the

Figure 1.1: Artist impression of the Atalanta bug.
design allows the wings to move in aerodynamically efficient patterns [7]. The thorax primarily induces the wing flapping motion while wing rotation (pitching) and wing up and down movement (heaving) are primarily passive. Efficient lift production using passive pitching and heaving is studied by Q. Wang. Control of hovering and flight will be done by adjusting the lift of the individual wings. Insects do this with small muscles at the base of the wings. Selection and implementation of micro actuators for this means is currently studied by H. Peters.

1.2.2 Characteristics

The Flapping Wing Micro Air Vehicle (FWMAV) design was built and the lift production was examined while the mechanism was actuated with an electrical actuator (figure 1.2b). The mass of the device was about 1 gram, the generated lift was 8.75 mN, almost 1 g, at an eigenfrequency of 27 Hz. The amplitude of motion of the ring structure was 3 mm in both directions. The designer poses that the lift production can be doubled by only improving the wing’s design and that fabrication improvements could increase the performance. It was observed that the structure is heavily damped. The wings form the dominant part of the equivalent inertia in the thorax-wing structure. The resistance of the wings has little influence on the natural frequency of the body. Insects have a Q factors of 6.5 to 19, this system has a Q factor of about 2 to 3.

Advantages

The resonating body FWMAV has the following advantages [7]

- Flapping wing vs. fixed and rotary wing:
  - When moving to smaller scales: hovering and slow moving flight becomes increasingly interesting in sense of energy usage.
  - Fixed-wing aircraft need ‘high’ speeds to stay airborne, high speeds limit indoor usage due to short reaction times needed for the control.
  - More silent and robust compared to rotary wing flight.

- Resonating body:
  - The indirect drive system that is used is energy efficient.
  - Steering of wings is decoupled from the energy input.
  - Flapping wings have enough possibilities to control all movements.

1.3 Power supply

Generally, MAVs are driven by electric motors that are powered by batteries. The limited energy density of batteries limits the flight time, further it is complex to make high power density electrical actuators at small scale. A. Meskers performed a research to find an alternative way to drive the MAV by selecting
another energy carrier [41]. Not only the carrier itself should be energy dense, but the complete system should be advantageous for the MAV, also after conversion from stored to mechanical energy, in terms of its power density and its energy density.

1.3.1 Energy carrier

All known energy carriers were compared by Meskers [41]: batteries, fuel cells, protein metabolism, liquid fossil fuels, etc. Chemical energy represents a group that has a high energy density and is still practical to use. Liquid chemical energy is released by a chemical reaction: combustion or catalysis. At small scale catalysis is preferred, as combustion needs mixing of two components (fuel and oxidizer) and combustion of this mixture, which involves a flame front. Both of these processes are slow and difficult to carry out at smaller scale. Catalysis takes place when a fuel (mixture) is brought into contact with a catalyst, this causes the fuel molecules to break apart. The catalyst speeds up the reaction mechanism, but is not consumed during the reaction. Exothermic catalytic reaction is possible for a group of mono-propellants which avoids the problem of mixing. From this group of fuels, hydrogen peroxide (HP) was selected because of its non-toxicity, its liquid state at room temperature and the fact that it is well researched as a fuel for all kinds of applications. Hydrogen peroxide decomposes into water and oxygen via an exothermic process. Many catalysts are available and high reactivity was measured for some transition metals and metal-oxides. There are many examples of propulsion systems, actuators and other micro (biological) motors based on hydrogen peroxide. All together hydrogen peroxide has reasonably high energy density and allows for a very robust and simple conversion system.

1.3.2 Chemical decomposition

According to Kapteijn and Meskers, [28, 41] manganese oxide shows the highest activity for hydrogen peroxide decomposition. A. Meskers manufactured various catalyst surfaces using the method of Kapteyn [28]. Reaction experiments were performed with droplets of hydrogen peroxide and multiple reaction parameters were recorded. The production process consisted of spin-coating a zirconium oxide layer on a porous ceramic, then impregnating it with a precursor which was aqueous manganese nitrate or manganese acetate. Multiple layers of the solutions were applied and dried was performed in between coating and the impregnation steps The sample was baked as a final step in order to activate the catalyst. The samples were tested with droplets of 30\% wt hydrogen peroxide. During the decomposition: pressure, temperature and reaction time were measured. Manganese oxide catalyst from the manganese acetate precursor lead to the fastest reaction time (70 ms) and the highest peak pressures (13 kPa). This was for a droplet of 22 µl, it was expected that a smaller droplet size would decrease the reaction time. A relation was found between the decrease of reaction time and the increase of reaction pressure. The reaction time can further be decreased by using smaller droplets and by increasing the concentration of the hydrogen peroxide. Static pressure increase after the reaction indicated that the reaction efficiency is near 100 \% due to the reacted oxygen. Fast condensation of the evaporated water indicates that a cyclic process using the short term high pressure has an advantage.

1.3.3 Work generation

T. Van Wageningen made the first steps for the Atalanta’s actuator design with the analyses of three concepts with different thermodynamic cycles [51]. In order to determine the actuator size, the required power input of the FWMAV was estimated by modelling the forces acting on the wings during a flapping cycle. A power consumption of 0.5 W was found for generating four grams of lift in hovering state. Next, the fuel consumption was derived with an estimation of the engine efficiency. Two grams of fuel give a flight time of about 16 minutes, for an engine efficiency of 5 \% and pure hydrogen peroxide fuel. Objective functions for the optimization of the engine were derived. Minimize:

\[ m^{3/2}/\eta, \]

while keeping the constraint:

\[ P_{out} = P_{hover}. \]

Chemical energy can be converted into heat, gas and/or light, there are many ways in which these can be converted into work. Three engine concept were analysed by Wageningen: an internal decomposition
expansion engine an external decomposition heat engine and a Tesla engine. The first two engines are cyclic the latest is rotary, all concepts though, could be elaborated in both ways. Various thermodynamic models were used to evaluate the concepts.

**Two stroke pressure engine concept** The concept is an internal catalytic decomposition engine, it consists of two identical expansion chambers. Internal combustion engines at micro scale often suffer from leakage and friction, to avoid this, the engine is carried out with a flexible membrane. The power density and efficiency are estimated using different models. The final model neglects: fuel pumping, viscous forces of fluid flow and the exact dynamics the fuel droplet decomposition.

The model used an operation frequency of 30 Hz and calculations showed that hydrogen peroxide decomposition was sufficiently fast for this frequency, taking into account small droplets or high fuel concentration. Compression ratios of 3 and 2 were chosen for an optimistic and a pessimistic set respectively. The results are displayed in Table 1.1. The performance found is suitable for the Atalanta MAV actuator. The exhaust temperature of the optimistic set is 130°C, which is the major cause of energy loss. An expected problem is fluid build-up in engine. The power density of the combustion engine scales with length scale.

**Tesla turbine concept** A Tesla engine converts kinetic energy to mechanical work by aerodynamic forces that act on rotating disks. Reaction products are delivered at constant rate and gain momentum by expansion. This engine was examined by using a one dimensional model of a moving belt with laminar air flow over it [12, 51]. The performance of the Tesla turbine is related to the change in pressure over the turbine. Higher difference increases the power, but it decreases the efficiency. With a pressure difference of 1 Pa, a maximum power output of 8 mW was achieved with an efficiency of 14%. The university of Berkeley tested Tesla turbines at the Atalanta scale. With a pressure difference of 10 kPa, they achieved a power output in milliwatts with a maximum efficiency of 40%. The maximum power output was at an efficiency of 10% [32]. Because of the trade-off between power and efficiency, the proposed Tesla turbine was not suitable as the Atalanta actuator.

**Heat engine concept** The heat engine that was analysed, is a Carnot heat engine with one cylinder at the hot reservoir and two cylinders at the cold reservoir. The Carnot theorem states that if the temperature difference between the hot and cold reservoir is higher, the efficiency of the reversible process will be higher. The maximum power is proportional to the heat transfer constant and the temperature of the reservoirs and is related to the reversible efficiency. Heat transfer rates become relatively larger at small scale, which allows for higher thermal energy transfer, but also for increased heat losses. A low heat transport Biot number has the result that the thickness and kind of insulation material does not help much. When the operating temperature is determined, a trade-off has to be made between Carnot efficiency and heat loss.

**Results** The model results are given for an engine with 7.5 cc air working fluid. The cold reservoir has ambient temperature, the temperature of the hot reservoir is 150°C for the optimistic set, and 100°C for the pessimistic set. The optimistic parameters gave a power output of 0.1 W with an efficiency of 11%. The pessimistic set gave a power output of 6 mW with an efficiency of 4%. The modelled power delivery is not sufficient for the FWMAV. In addition, the estimated volume and mass of the system was too large due to the costs of an extra cycle. The power output scales linear with size, so the power density increases. Multiple small heat engines might be an option.
1.4 Research goal

Achieve a proof of concept for the working principle of a catalytic decomposition actuator, specifically designed for the Atalanta FWMAV.

1.4.1 Requirements

Requirements for the Atalanta main actuator are:

**Qualitatively**  Deliver work to the FWMAV such that:
- the desired resonant mode of the FWMAV is exited and
- the desired amplitude is maintained.

In a way that:
- the energy density advantage of liquid chemical energy, compared to batteries is maintained, taking into account the actuator efficiency.
- And the weight of the dry system has to comply with the designed FWMAV.

By using:
- hydrogen peroxide as an energy carrier,
- a solid catalyst as a decomposition agent.

**Quantitatively**
- Mechanical power required: 0.5 W
- Desired amplitude and variance: 3 +/- 0.5 mm
- Actuator frequency: 27 Hz
- Actuator efficiency: 2-5 %
- Allowed actuator mass: 1 g
- Allowed fuel mass: 1 g

1.4.2 Approach

The progress made in the actuator design is done by diverging and converging twice. Chapter one and two provide the knowledge and background information for the analyses that is performed in chapter three. The analysis converges to a an functional design description in which fundamental choices are made for the actuator. The description is translated into a design with actual components, the working concept, the elaboration of separate components has to be examined in more detail. For two important components, this is done in chapter five and six. An attempt to integrate the selected components and converge to a proven solution is explained in chapter seven.
Chapter 2

State of the art micro power supply

This chapter provides an update on the development of energy carriers and converters that are relevant for this project (2.1). Followed by an overview of the knowledge that was gained in the development of these converters (2.2). The link with the Atalanta actuator is discussed in the final Section (2.3).

2.1 Current developments

This section provides an overview and some examples of state of the art batteries, mono propellants, micro combustion engines and reactors.

The development of micro and meso power supplies is not only stimulated by demands of MAV’s. The market request increases rapidly with the growth of portable devices such as cellular phones, notebook computers and personal power. Unfortunately, the energy density of the existing batteries is still low. The lack of compact, durable, efficient, light weight, and instantly rechargeable power sources greatly limits the development of micro-mechanical and chemical systems for various applications. Therefore the development of alternate power sources is increasingly stimulated and progressing for about a decade [26].

2.1.1 Energy carrier development

Hydrogen peroxide was chosen as the energy carrier for the Atalanta actuator. In order to compare, an example is given of a well performing small battery. To give a further perspective, some alternate mono propellants are mentioned.

2.1.1.1 Batteries

The most advanced lithium ion batteries of today have an energy density of about 200 Wh/kg [64, 27].

Stand alone electrical actuation is used by the DelFly micro, which is a flapping wing MAV. It’s energy source is a lithium polymer battery of 1 g, which provides a flight time of three minutes [38]. The latest of these type of batteries can deliver an energy density of 170 Wh/Kg and a power density of 4000 W/Kg. Batteries of 1 to 4 gram are less efficient, but are relevant for MAV’s, they still attain 130 Wh/Kg and 2600 W/Kg. More modern battery concepts like the Lithium Sulphur type can almost double the energy density, but they still do not match the required power density [10].

2.1.1.2 Mono propellants

Mono propellants consist chemicals that do not require an oxidizer to release their stored chemical energy. Much work was done in the US in the 1950s and 1960s to attempt to find better and more energetic mono propellants. In most cases, researchers came to the conclusion that any single substance that contained enough energy to compete with bi propellants would be too unstable to be handled safely under practical conditions [57]. A well known and broadly used chemical which is highly toxic and explosion sensitive is hydrazine, it has an energy density more than 6 times that of hydrogen peroxide, 19.5 MJ/kg compared to 2.93 MJ/kg.
The development of fuels for future satellite propulsion resulted in safer and still energetic mono propellants. The so-called green propellant’s were developed based on the oxidizer Ammonium Dinitramide. A mixture with water and methanol fuel gained a specific impulse of 2500 Ns/kg compared to 1600 Ns/kg for hydrogen peroxide [59]. Even compared to hydrazine fuel and thruster systems, the new fuel including system resulted in improved performance and enhanced volumetric efficiency [46]. A catalyst could be used for decomposition, in a similar way to that of hydrazine. Another propellant class was reported [3], known as AFM315, which has an energy density close to twice that of hydrazine and has outstanding safety and hazard properties.

2.1.2 Energy conversion at micro scale

An update is given of relevant energy converters at micro, meso and macro scale. Combustion engines, reactors and hydrogen peroxide specific converters are addressed. An example of a meso scale electrical actuator is given as well. The overview of the micro combustion engines and reactors is taken from review "Microscale combustion: Technology development and fundamental research" [26].

2.1.2.1 Thrusters

Micro thrusters were produced using various micro-fabrication technologies such as stereo lithography [62], low temperature co-fired ceramic taping [61, 39] and silicon based MEMS fabrication techniques. Various fuels are being used: mono propellants [34] such as hydrogen peroxide and hydrazine, as well as hydrocarbons. Micro-thrusters may have much higher energy density than that of conventional engines. An example of a MEMS thruster that used bi propellant fuel was shown by London et al. [36] (figure 2.1). Life time of MEMS thruster devices is short due to the low thermal stability of silicon at high combustion temperatures (1600 to 1800 K). Therefore high melting materials were used like metals [64], ceramics [65], and quartz [21]. The combustion efficiency and flame stability is improved considerably. However, the wall heat loss is still large and the combustion efficiency remains low. Also there are fabrication and start-up problems [26].

2.1.2.2 Internal combustion engines

There are several designs of micro internal combustion engines, including: gas turbines, rotary engines, and piston engines.

Turbines Micro turbines were fabricated using conventional techniques by Tohoku University in cooperation with IHI Corporation [24, 48] and using MEMS techniques by MIT [1, 16]. The turbines run on hydrogen, methane and other hydrocarbon fuels. Epstein et al. made a micro gas turbine generator [16].

The MIT gas turbine engine has a diameter of 21 mm and thickness of about 4 mm, it weight in total less than 1 g. 10 to 20 W of power was achieved at 1.3 million rpm. The working of an integrated device - combustor, turbine and generator - is not yet confirmed.
Figure 2.2: Micro piston engines. Left: nominal 10W MICE generator design [31]. Right: Knock piston engine [26].

Wankel rotary At UC Berkeley, Fernandez-Pello and co-workers [19, 18, 20] designed Wankel rotary engines at different scales. The meso scale version had a rotor size of 10 mm, it produced about 30 W of power. Two micro versions were constructed with rotor sizes of 1 mm and 2.3 mm. The goal is to produce 10 to 100 mW of mechanical power with an engine chamber size below 1 mm$^3$ [17, 20]. The 2.3 mm rotor version produced about 3.7 W of power at 9000 rpm, it obtained a thermal efficiency of about 0.2 % [18]. Hydrogen and liquid hydrocarbon fuels were used.

Free piston Free piston engines were designed in different configurations, using different ignition methods: Honeywell [1] used homogeneous charge compression ignition (free piston knock engine Figure 2.2 left). Aerodyne Research used glow plug assisted ignition and air pre-heating [5]. Ignition was used on both sides of the cylinder [1]. The free piston engines were integrated with electrical power generators that used a magnet in magnetic field [1] or a linear electric alternator [25]. Various fuels were used: liquid hydrocarbon fuels [11, 22], heptane, butane, and diesel [63, 2] and JP-8, diesel by Annen [5]. An example is an IC engine, developed by Aerodyne Research, that was produced and tested at different sizes [45]. The Miniature Internal Combustion Engine (MICE) can provide electric power at much higher energy densities than batteries. MICE is a free piston system having a two-stroke engine, a spring, and a linear alternator (Figure 2.2 right). The system operates at the resonant frequency which leads to very low frictional losses, even when running without oil lubrication. A nominal 5 W engine weights 15 g, has a piston diameter of 3 mm and a stroke of 5.5 mm. Successful tests were carried out at 440Hz which resulted in 0.88v and 0.59 W of electrical power at efficiencies of 1.7 and 1.3 % respectively. Propane fuel was used.

2.1.2.3 Heat engines

A heat engine is an external combustion engine that converts heat to mechanical power via a closed thermodynamic cycle.

An example is a MEMS based heat engine, constructed at the Washington state university. The engine consists of two flexible membranes encapsulating a volume of saturated working fluid (Figure 2.3a). A thermal switch is used to intermittently reject heat from the engine to a cooling sink. The engine is shown to produce 1.0mW of mechanical power when operated at 100 Hz. The generator weighs in the order of 10 mg. The theoretical Carnot efficiency for this device is about 5 % due to the limited temperature excursions of the engine's working fluid and the ability to heat [53].

At Washington State University, another MEMS based heat engine was developed, that showed the first electrical power generation by a dynamic micro heat engine (Figure 2.3a right). The heat engine used a novel thermodynamic cycle, mechanical power was converted into electrical power with the use of a thin-film piezoelectric generator. With a thermal power input of 1.45 W, 0.8 µW of electric power was produced. The membrane resonated at its eigenfrequency of about 240 Hz. The membrane featured sides of 3 mm, and a thickness of 1.3 plus 1.1 mm for the silicon and PZT respectively [54].
2.1.2.4 Reactors

There are sole reactors which can be combined with for example heat engines or turbine engines and there are reactors that are combined with electrical generators, such as: thermoelectric, thermo-photovoltaic and piezoelectric devices to directly obtain electrical power[26]. Based on recycling of excess enthalpy from burned gas, different kinds of Swiss-roll micro combustors have been designed (Figure 2.3c) [52, 45].

Disk-shaped swiss-roll micro combustors were developed for heat sources purpose by the Tohoku group [31, 30]. Prototypes with outer diameters of 64, 45, 26 and 20 mm were made, with a total thermal efficiency that ranged from 60% to 85%. The smallest devices were fabricated in stainless steel by EDM. Model predictions agree well with measured performance.

Liquid fuel-film combustors were developed by [44, 35, 43]. The fuel is injected as a liquid film on the inner surface of cylindrical combustor and swirling airflow provides effective fuel vaporization. It enables reduction of heat losses by redirecting heat toward film vaporization and cools the combustor walls. It was shown that internally stabilized flame was attained for liquid fuelled flames but not for gas-fuelled flames.

Demonstrations of direct electrical power generation was given by catalytic or non-catalytic combustion combined with thermoelectric and TPV devices. The absence of moving parts gives results in zero friction losses. Figure 2.3c shows a methanol-fuelled catalytic micro-reactor system, consisting of platinum on anodized aluminium with a commercial thermoelectric device. It successfully produced 0.65 W of electricity with a total efficiency of 1.1% [29]. Another catalytic combustor with commercial thermoelectric device, and a 0.8 mm inner diameter ceramics tube reached 3.0% total conversion efficiency, which exceeds the typical value of batteries [47]. The his device generated 161 mW of electricity with 5.37 W, of fuel supply.

2.1.2.5 Electrical generator

Developers of the DelFly micro researched the possibilities for a power supply for their flapping wing MAV. They found that a high RPM electric motor is still the best solution yielding a favourable power density, in combination with a gear set plus crank mechanism to match the rpm and the flapping frequency of the wings[10]. Use of a linear or reciprocating actuators was discarded because of limited power of weight ratio. After overheating and wear problems of a brushed motor, a brushless motor was used that reached higher efficiency (59%) and higher power density (> 1 kW/kg). The absence of wearing parts, other than the ball-bearings, made the reliability of the motors several orders of magnitude better than their brushed counterparts. The engine weights 0.45 g [38].

2.2 Theory and scaling of micro converters

Knowledge of physics and scaling effects, combined with knowledge gained during the development of micro converters, provides insight in the possibilities and issues of micro scale energy converters. This section provides a summary of the theory and practical knowledge on this subject. Theory on scaling applied on micromechanical devices is given by William Trimmer [49].
Combustion engine & scaling

Compared to 2003, a much better fundamental understanding is gained on micro scale combustion such as heat recirculation, flame-wall thermal and kinetic couplings, new flame regimes, fuel/oxidizer mixing, flame instabilities, and non-equilibrium transport. After one decade of research and development, the study of micro-scale combustion is moving into new directions [26].

Leakage & Friction  Leakage is a significant potential loss mechanism at engine sizes smaller than 20 W. For sizes above 100 W friction and pumping losses are second to heat transfer as a major loss mechanism. For IC piston-cylinder engines, below a power output of 750 W, most designs do not use piston rings to avoid excessive frictional losses at the high cycle speeds, which is required for good power density. A close tolerance fit is required, the tightness of this fit is limited by surface finish, alignment, and the need to keep frictional losses at a moderate level. A gap of 2.5 µm or lower is required to keep the leakage fraction to 1% or less for a the 10 W engine. The MICE engine proved that low friction operation is possible with intense combustion and without oil lubrication, using a solid film lubricant. The tests demonstrated The piston and cylinder showed no signs of wear after the tests. [6]

In the drive mechanism of the DelFly Micro, it was noticed that smaller systems had relatively more friction than a larger one. To enable a smaller MAV of about 5 cm (DelFly nano), some parts of the design should undergo a thorough change. For example the drive mechanism and the crank-mechanism actively operates the wing during all phases of the flap. Instead, natural systems and artificial systems exploit the resonance of the system. Designing a resonant drive mechanism may be a necessary step towards smaller sizes [10].

Heat transfer  Heat transfer is a significant loss mechanism for miniature engines. For miniature engines of a size of roughly 50 W and less, the engines will need to be insulated to avoid excessive heat loss unlike larger engines. The ideal Otto cycle has an efficiency of 45 % for a compression ratio of 10, with the effect of heat loss this will be reduced to 40 % for a 1 kW engine and 32 % for a 1 W engine [6]. To improve the thermal efficiency and combustion stability of micro combusters, thermal management and the use of catalyst are important aspects. The large surface to volume ratio in small scale, can be used to achieve recirculation of heat and with for example the vaporization of fuel.

Combustion and mixing  As combuster size decreases, the flow Reynolds number becomes very low (1 to 100) [17], the molecular diffusion is the dominant mechanism for viscous flow and fuel-air mixing [13, 8, 37]. Combined with the increase of surface area and the reduction of characteristic thermal inertia, this results in reduced mixing, enhanced wall heat loss, wall flame thermal, wall flame kinetic couplings, and skin friction. The flame dynamics will dramatically change and new combustion phenomena arise such as flameless combustion, weak flame propagation, flame street formation, kinetic extinction, pulsating and spinning instabilities [6].

Combustion quenching  Combustion quenching is a significant loss mechanism for engines smaller than 20 W. The quenching distance scales approximately inversely with pressure. The quenching distance also decreases with increasing temperature as a result of the increase in flame speed with temperature. Quenching losses for several fuels can be estimated using tabulated quenching distances [6].

2.3 Conclusion

The high energy density of hydrocarbon fuels creates a great opportunity to develop combustion based micro-power generation systems to meet increasing demands for portable power devices, micro unmanned aerial vehicles, micro-satellite thrusters, and micro chemical reactors and sensors [26].

Energy carrier  Hydrogen peroxide was chosen because the fuel is relatively safe compared to other mono propellants. New ADN based mono propellants were developed with benefits similar to that of hydrogen peroxide and with energy densities up to twice that of hydrazine.
**Reactors**  Efficiencies up to 99% were shown for small chemical reactors. The phenomena and problems occurring in micro scale combustion are understood much better, designs were made that avoid problems and make use of new phenomena. Direct integration of reactors with thermoelectric cells have given battery competitive energy densities.

**ICE**  A lot of progress has been made in the development of ICE's. Experience has lead to greater understanding of the characteristics on micro scale combustion and mechanical or electrical energy generation. The efficiency remains lower than at macro scale because of increased losses due fundamental scaling laws and fabrication limitations. Very high power densities of work generators were reported, but for a stand-alone power unit, an undetermined amount of weight is still to be added for the additional required components, such as reactors and pumps.

**Electric conversion**  The DelFly project shows that electricity is still a feasible power source at the Atalanta scale. Problems in efficiency and durability increase when applying the electrical actuator on an even smaller scale. Developments have already shown that small combustion-generator devices can outperform batteries.

**Conclusion**  The need to design a power dense and efficient actuator is as important as the selection of a high energy density carrier. Comparing the efficiencies of electric and combustion/decomposition engines, it is doubtful whether a converter based on hydrogen peroxide fuel will give an advantage over electric energy. Compared to using hydrocarbon fuels or other high energy density mono propellants, the use of hydrogen peroxide offers the advantages of: avoiding combustion and mixing problems, dealing with an environmental friendly, easy obtainable and non-hazardous fuel and having an easy means of reaction. This makes the use of hydrogen peroxide an interesting source and conversion fuel and a feasible solution for a simple actuator design. Furthermore it gives an interesting platform to practice new meso-scale chemical-reaction concepts for later use of higher potential fuels. The first actuator units are not likely to exceed 1% of overall conversion efficiency, therefore 1% is used for dimensioning in this project. The efficiency will increase during the actuator development, it is expected that an efficiency of approximately 5% can be achieved in the end.
Chapter 3

Functional design

Designing is making choices. For the Atalanta actuator, some choices are limited by requirements and other choices are fixed by the resonating body FWMAV design. A lot of choices are still to be made in defining an actuator design that fulfills the requirements. There are various tools that can help to make decisions like calculations, models and simulations. During this chapter, mainly the tools reasoning and comparison are used to make design choices.

In Section 3.1 the approach is stated and the structure of this chapter is clarified.

3.1 Approach

Situation Designing a meso scale hydrogen peroxide catalytic actuator is complex because of various reasons:

- Production: conventional techniques become less accurate compared to the typical feature dimension. MEMS fabrication is limited in 3D production and material use.
- Physical phenomena:
  - friction and wear of sliding surfaces increases
  - fluids behave different from macro scale
  - reaction speed changes
  - heat loss and insulation difficulties
- There is not much experience with chemical decomposition engines at this scale.
- The experience at this scale is that efficiency and power density decreases compared to macro scale devices.
- There is little experience on reciprocal (catalytic) reaction, which was the preferred means of decomposition.

Approach Because of this complex situation, it is important to take an open approach to the problem such that new, creative solutions can arise. Ideally, one would examine all possible and unconventional solutions in detail, rate them and then make a choice. This is not possible taking into account the huge amount of solutions that are possible, not speaking of those that are not yet developed. Therefore it was decided to start the research with a functional description of the design. This description consists of the primary and secondary functions that the actuator has to fulfill (Section 3.3). They are defined and evaluated in sections 3.4 and 3.5, using the boundary conditions (Section 3.2) and requirements (Section 1.4). Different concepts are shown in 3.6, a choice is made in Section 3.7.
Process and argumentation  It is started with an open approach but the design has to be narrowed down specifically for the Atlanta actuator. The following steps are taken:

- All including descriptions are used in the functions such that all possible designs are included.
- Include from the start the direction that is given by the boundary conditions and requirements.
- Confin to and characterize groups of sub-solutions.
- Decrease design space: avoid drowning into the endless possibilities of processes, structures, materials and production methods.

With the limited knowledge and simplified descriptions, it is not certain that the best solution is found, the method is used to find a feasible, promising direction.

3.2 Interpreted actuator criteria

The actuator requirements are defined in Section 1.4, this section explains what further design requirements are extracted from the FWMAV design and boundary conditions.

3.2.1 System boundary

It is important to define what the functional boundary is of the actuator part of the FWMAV. In Section 1.4, it was described that the actuator needs to supply work to the FWMAV. The complete energy flow from recharging to work delivery is assigned to the actuator design, also the actuator suspension to the FWMAV is included. This is because a light, high performing stand-alone actuator system is required. The only way to achieve this is with a high degree of system integration. This work does not cover the design of this complete system, but it is tried to take into account all the aspects within the defined boundary.

3.2.2 Coupling to the FWM

A lot of actuator requirements follow from the FWM design, interpreted requirements are explained below.

General  The FWM needs a work input of certain frequency and magnitude, in a certain direction at a certain location such that the amplitude of the intended resonating mode is maintained. This is important because the wings are designed to make a given flapping motion, which allows an efficient lift production. The idea is that the resonance frequency and power consumption of the system barely changes during wing lift control. Therefore, it is assumed that a certain average work input is required, independent of the velocity changes of the bug [7].

Damping  The Q factor of the resonating system is low, about 2 to 3, due to the large aerodynamic damping. It follows that when the system is in resonance, the amplitude will decay fast when the system is not excited externally. When \( Q = 2 \), 50% of the stored energy is dissipated in a cycle, this results in an amplitude decrease of 30%. Therefore, it is desired that energy is supplied during each resonating cycle, such that reliable lift production is achieved.
**Actuation location and direction** Other eigenfrequencies could be excited depending on the position(s) on the FWM where the work is delivered to. Assumed is that the whole structure can be excited from the resonating thorax, as was done with the electric actuator by Bolsman (Fig. 1.2b). Locations are displayed by the dotted circles on Figure 3.2. Important is that force is actuated along the velocity vector of the FWM.

**Actuation magnitude** Certain input patterns are suitable for supplying work to the FWM. Proposed patterns are displayed in Figure 3.2. There is one criterion for the input: the total work that is produced during one cycle along the velocity vector of the FWM, should be equal to or larger than the average power consumption of the FWM.

A certain work input pattern is required to obtain the exact designed wing positions and velocities at each moment of the flapping cycle. This could be a sinusoidal input or an input that opposes the work done on the system by damping. Anything different from this input is non-ideal and will potentially excite other eigenfrequencies. Still, for allowing a great design freedom, all the suggested patterns are allowed. When the MAV is starting up and the actuator is consistently producing the average required power of the FWM, the desired amplitude will be reached after a certain amount of time. It is assumed that a slight overproduction in power will not disturb the resonating system, the compliant system will probably dissipate more at amplitudes higher than required, such that the amplitude remains around the intended value.

**Frequency and synchronization** The work input of the actuator should be synchronised with the resonating motion of the FWM. Otherwise the work produced does not excite the resonating mode, but damps it, and again, other modes can be excited. This synchronisation can be done by 'internal' or 'external' driven timing of the actuator. When the work production of the actuator is directly coupled to the FWM then it is 'externally' synchronised (feed-forward control). The actuator has internal synchronisation when it has its own clock or when the output is actively controlled (feed-back control). Timing with an internal clock without feed-back control is not feasible, for the frequency of the FWM can change slightly due to mass changes (fuel storage), stiffness changes (wing control) or amplitude changes (non-linear stiffness). This causes the two systems (actuator and resonating body) to operate out of phase.

**3.2.3 Catalytic decomposition**
As explained before, Meskers searched for a suitable energy carrier for the Atalanta FWMAV. The decision for hydrogen peroxide fuel and a heterogeneous (solid) catalyst are adopted for the actuator. The choice for HP was explained in the conclusion of the first chapter. The choice for a solid catalyst is mainly because of the high reaction rate that can be achieved, the avoiding of micro scale mixing problems and because of the recent successful experiments.

**3.2.4 Decision priorities**
For the decision of a concept, the following aspects and arguments are important to take into account:
3.3 Actuator Functions

3.3.1 Primary functions

We will start the design process with a basic description of the actuator, by using the known activities that have to be carried out. With a yet undefined method, mechanical work has to be produced from the reaction that occurs when fuel is brought into contact with a catalyst. This is displayed schematically in Figure 3.3. The most basic functions are: storage, reaction and generation. They are explained below. Possibly, many additional functions are needed.

1. Storage The FWMAV has the energy form: ‘internal energy’. It is required that the aerial vehicle can fly for a few minutes autonomously, therefore the device needs to be able to store a certain amount of energy, i.e. fuel.

2. Reaction During the process there is a moment where fuel meets the catalyst, that is where the decomposition takes place. Internal energy is transformed into potential energy in the form of reacted products and heat.

3. Generation The final step is called ‘generation’, potential energy is converted to work.

3.3.2 Secondary functions

For a proper working of the actuator, secondary functions are needed that couple the main functions. The requirements on these additional functions depend heavily on which primary functions are chosen. These secondary functions result in ‘overhead’ for they increase the actuator’s mass and decrease its efficiency and netto power production. The secondary functions are further discussed in the section 3.5.
Patterns of energy flows  As discussed in Section 3.2, the actuator has to be compatible with the FWM. Somewhere in the design, a synchronization step has to take place, such that this is achieved. The way in which these energy flows are arranged is essential because it determines what specific components can be used and what additional functionalities are required. All activities in the actuator can be performed in a continuous or non-continuous manner. Continuous in this sense means that the task is performed with a sustained energy flow. Non-continuous means an energy flow that is not sustained. Both types can have all kinds of flow shapes, but only certain patterns are desired for the FWM actuator. The shape of the energy flow in the actuator is assumed to be constant or reciprocal, because the FWM needs work input each cycle and the actuator needs to be reliable in providing this. Figure 3.4 shows three flow patterns; continuous, non-continuous plus cyclic and non-continuous and non-cyclic. Of these only the first two are accepted. The constant rate might be slightly changing as well the cyclic pattern, but it is important to make this fundamental difference.

Figure 3.4: Energy flow patterns within the actuator, examples are given of the three general groups. a: continuous, b: non-continuous, reciprocal, c: non-continuous, irregular.

3.4 Primary functions

A morphological overview of the functions is given in Table 3.1. The options for the functions that are shown can be selected independently, however, some combinations are not feasible. The functions and variables will be treated in this chapter.

3.4.1 Storage

The storage function has to be able to contain two grams of fuel or less. Further, it requires one or more openings for refuelling and provision of fuel to the next function. Large energy buffers after the storage function is not desired, so the storage has to provide an average fuel rate over every FWM cycle. This flow of hydrogen peroxide can be continuous or reciprocal. Control of this fuel flow is an additional, intermediate function. This all has to function under accelerations and rotations of the MAV.
3.4.2 Reaction

Reaction takes place when the fuel meets the catalyst, which result in reaction products which carry potential energy in the form of heat (Figure 3.5). The reaction can be executed in a continuous or in a non-continuous, reciprocal way. The second involves a reaction rate pattern and a frequency, the frequency is synchronized to the FWM or not. There are a few implicit things that can be stated about these two methods, the origin of the properties lies in the steady or a unsteady reaction that follows from the continuous or non-continuous flow. The reaction defers in: temperature, pressure, reaction rate and velocity. These influence the mass and size of the component and the reaction its reliability, potentials and losses. Considerations are explained below.

Figure 3.5: Reaction function schematic

**Reaction rate** For reciprocal reaction: not all the catalyst material is used simultaneously, more catalyst material is required to achieve sufficient conversion. The mass and size of the function is larger. Continuous reaction results in developed, steady flows and continuous reactions are generally more efficient and reliable.

**Temperature, pressure and fluid velocity** Reciprocal can imply short duration temperature increases, which means little heat loss but more thermal stress. Changing pressures with probably higher peaks results in a higher structural load. Changing velocities is likely to result in more flow losses.

3.4.3 Generation

There are many variables that can be specified for the generation function. Three basic generator variables are discussed here: generator process type, generator motion type and the generator frequency. Figure 3.6 shows the schematic situation, Table 3.3 displays the various generator options, with inputs and outputs, resulting from the generator variables. The following three subsections give explanation and argumentation for the variables.

3.4.3.1 Generation frequency

The frequency is related to the output of the generator. It is evaluated as a separate variable, because it influences the performance of the generator a lot. It is also relevant for the coupling with the type of reactor and the coupling to the FWM, which will be discussed in Section. For the rotary type, the frequency is the rotation frequency. The frequency of the linear type combined with reciprocal input, is that of the reciprocating cycle, the frequency is limited and directly determined by the input. The linear motion type combined with continuous energy input has no, or a very low frequency (explained in 3.4.3.3).

Figure 3.6: Generation schematic with input, output and generation variables.
Primarily, the frequency influences the mechanical power produced by the generator, the power increases linearly with frequency if the generator produces a constant torque or work per cycle. Often the work or torque decreases at higher frequencies and losses due to friction and (aerodynamic) flow increases. The weight of a generator is mainly coupled to the torque or force that is produced. Therefore, a generator is usually lighter at a higher frequency for the same power output. Three frequency ranges can be selected for the generator. There is a coupling benefit if the generator frequency is the FWM frequency. A frequency higher than the FWM has the benefit of a potential higher power/weight ratio. A frequency smaller than the FWM is not desirable, for it lacks both benefits.

3.4.3.2 Generation process type

This variable specifies which thermodynamic process is used by the actuators in order to obtain work. As discussed in Section 1.3.3, there are three basic processes that can be used: the external decomposition engine, the internal decomposition engine and the momentum engine. These types are distinguished because their processes can be characterized as a group and they can be examined by a thermodynamic model. In reality multiple processes can be combined. It is assumed that one process is used mainly and that full hybrid engines are not desirable in terms of robustness simplicity and power density. The process types are characterized as follows:

- Pressure engine: Reaction gases are expanded to obtain work.
- Heat engine: Expansion takes place in a separate cycle, multiple heat exchangers are needed.
- Momentum engine: Very different concepts are possible. In general, there is a relation between mass and efficiency.

Power to weight ratio Models by T. Van Wageningen (Section 1.3.3), give an estimation of the power, efficiency and power to weight ratio for the three generator process types. The summary is displayed in Table 3.2, for a pessimistic set of boundary conditions. The frequency is fixed for the pressure engine at 30 Hz while the frequency of the other two engine concepts were optimized. Other concepts can be designed from these process types than those proposed, important alternatives are given by choosing other options for the other generator variables.

<table>
<thead>
<tr>
<th>Process Concept</th>
<th>Pressure</th>
<th>Heat</th>
<th>Momentum</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-stroke expansion</td>
<td>4</td>
<td>0.008</td>
<td>0.006</td>
</tr>
<tr>
<td>Efficiency</td>
<td>36 %</td>
<td>14 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Power / weight [W/kg]</td>
<td>245</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.2: Pessimistic modelled results from Wageningen [51], for three engine concepts embodying the generator process types.

Efficiency Table 3.2 gives the efficiencies that were achieved in the modelled concepts. Some remarks are given below.

- Heat engine: The theoretical Carnot efficiency increases as the temperature increases, but meanwhile the heat loss increases. Theoretically a 20% efficiency is possible for a hot body of 100°C. Multiple (smaller) heat engines could be used to increase efficiency, but this increases mass and complexity.
- Pressure engine: A reasonable efficiency can be achieved, but practical losses as leakage, friction and heat loss are probably underestimated in the model.
- Momentum engine: The efficiency of known systems is related to structural complexity and power density. A nozzle is a very simple generator yet very inefficient. The Tesla turbine is more efficient but has a more complex, heavier structure. The efficiency increases as the pressure difference over the turbine decreases, but then the power density decreases as well.
Table 3.3: Generator types organized using 4 variables: input shape, generator motion type, process type and frequency.

<table>
<thead>
<tr>
<th>#</th>
<th>Input shape</th>
<th>Generator Internal motion type</th>
<th>Process type</th>
<th>Output frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>continuous</td>
<td>rotary</td>
<td>h / p / m</td>
<td>function of load</td>
</tr>
<tr>
<td>2</td>
<td>reciprocal</td>
<td>linear</td>
<td>m</td>
<td>no frequency</td>
</tr>
<tr>
<td>4</td>
<td>reciprocal</td>
<td>linear</td>
<td>h / p / m</td>
<td>equal to input</td>
</tr>
</tbody>
</table>

**Losses** Additional to the modelled concepts with derived power and efficiency, some general statements can be made on losses within the different process types.

- Heat loss is a function of: temperature difference, surface area, time and heat transfer coefficient. The heat engine has a relative large body for losses via conduction: heat exchangers, additional work cycle and a hot reservoir. The Pressure engine has a hot body in which expansion takes place. The momentum engine usually features a fast transition from heat to pressure to momentum. The process is likely to have areas of continuous heat loss, the heat conducting surface can be limited.

- Fluid flow loss is a function of viscosity, velocity and channel size and shape. It is especially applicable on the momentum engine.

- Leakage depends mostly on ‘generator motion type’. The expansion of a heat engine is usually performed in a closed volume, so leakage can be avoided.

3.4.3.3 Generation motion type

The generation function can be performed in a continuous or in a non-continuous, reciprocal way. It has a great influence on the elaboration of the generator function. A continuous energy input can be converted into linear or rotary system. Practical generators are for example the nozzle of a thruster and the turbine of a turbosfan engine. Reciprocal generation can also be linear or rotary. Examples are the Wankel rotary engine and the piston-cylinder engine. The primary difference between linear and rotary is that the generator produces a torque or a force-stroke to supply the work. A short characterisation of the motion types is given here, more details can be found in Appendix A.

**Rotary** At micro scale rotary type engines suffer from leakage and wear, decreasing the efficiency and life-time. Power to weight ratios can be really high due to a possible high rotary frequency.

**Linear motion type + Reciprocal input** Many of the properties of a rotary generator are inverted for the reciprocal, linear generator. Problems of friction, wear, lubrication and leakage can - in principle - be avoided with a smart design. But the is limited.

**Linear motion type + Continuous input** The continuous and linear input is only practical for the momentum engine, for it can use inertia to provide a force. A very proven elaboration at various scales and also with the use of hydrogen peroxide is the nozzle. It is a very simple, robust and lightweight generator, offering a very high power to mass ratio.

3.4.3.4 Conclusion

The variables generator frequency, process type and motion type all have their influence on the properties and performance of the generator. The options within the design parameters can be characterized independently, but the choice of one parameter value can limit the choice within the others. A summary of the possible actuator types, ordered using the proposed variables, is given in Table 3.3. In total there are 10 feasible generator types. For the 6 rotary type engines the frequency is free. For the reciprocal, linear engine the frequency is normally determined by the input. This paragraph gives an interesting overview of the possible generator types from different view points. It shows that a balance has to be found between power density and efficiency, with important variables frequency and structural complexity.
3.5 Secondary functions

Figure 3.7 shows the primary actuator functions, they are coupled by the secondary functions indicated by numbers 1 to 4. Step 1 is not discussed here.

3.5.1 General

Generally, the secondary functions consist of the following parts:

- Transport: Liquid flow (fuel and water), gas flow (oxygen and steam), this includes refuelling. Transport at (4) is exhaust to the environment and transport of mechanical energy to the FWM.
- Dosing: Is required to ensure that in every cycle the correct amount of energy is converted.

Possible extra functions:

- Timing/switching: The energy flow in the actuator ultimately has to be synchronized with the FWM, therefore the energy flow needs in some cases a timed start/stop.
- Flow potential: Is needed to drive the transport of fuel.
- Buffer: For temporary storage of energy. Allows a change in the energy flow frequency and/or pattern.
- Mechanical energy conversion: For changing the work flow from the generator in terms of frequency, amplitude or motion type.
- Control: Can be applicable to various functions as timing and dosing. Can consist of feed-forward and feed-back control.

Integration With integration is meant the combining of functions into a single volume or component. The possibility of this depends primarily on the energy flows in between the main functions. At the end of the energy conversion process, the FWM needs the work to be supplied in the correct manner: reciprocating, with a certain frequency, amplitude, etc. as discussed in Section 3.1. For example, when the generator is synchronized to the FWM in terms of frequency, phase and motion type, then only very little overhead is required between the generator and FWM. On the other hand, when the generator is not synchronized it requires a lot of overhead, this could be: gears, a rectifier and linkages. The possible degree of integration influences the complexity, weight and loss in power of the secondary function and hence the complete system very much.

Primary as well as secondary functions can be integrated. Integration of functions could make transport and other secondary functions unnecessary.

3.5.2 Storage - Reaction

Two basic types of reactors were discussed: the continuous or the cyclic reactor. Both types include transport of the liquid fuel, a flow potential is required to let the fuel flow from the storage towards the reactor. The potential can be facilitated by a separate component or it can be integrated in the storage or in the reaction function. For the batch reactor, a timing/switching device is needed to provide control.
of the repeated reactions. Both reactor types require dosing of the fuel in order to provide the right amount of energy flow, hen it is assumed that no large buffer is applied after the reaction.

Integration of the storage and reaction function is possible, reacted products (potential energy) flow directly from the storage function. Reaction dosing and timing can be done with, for example, the catalyst amount that is in contact with the bulk fluid. It can be a very simple system, but there are some draw-backs:

- The reaction products are directly cooled down by the bulk liquid fuel, direct condensation of the evaporated water is likely to occur, the pressure peak of the reaction cannot be used.
- The catalyst material probably stays cool and remains wet, which results in a low reaction rate.

The conclusion is that integration is not desired at this position, because it is not likely to result in an efficient system. The extra functionality between storage and reaction is the smallest when continuous reaction is applied. For a batch reaction it is required that switching and timing is taking place at this stage.

### 3.5.3 Reaction - Generation

The overhead needed in between the reaction and generation functions varies according to changes in the energy flow pattern and frequency. Due to the reaction output and desired generation input, four different transitions can be made. Frequency options are: no frequency, FWM resonance frequency or other. All overhead options are visualized in Table 3.4. The generator variable 'motion type' (rotary or linear) does not influence the overhead. A driving force is required to drive the reacted products to the generator, in most cases this is provided by the reaction.

<table>
<thead>
<tr>
<th>reaction shape</th>
<th>reaction frequency</th>
<th>overhead</th>
<th>generation input shape</th>
<th>frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>continuous</td>
<td>-</td>
<td>buffer + timing</td>
<td>continuous</td>
<td>-</td>
</tr>
<tr>
<td>reciprocal</td>
<td>= FWM</td>
<td>buffer</td>
<td>reciprocal</td>
<td>= FWM</td>
</tr>
<tr>
<td>reciprocal</td>
<td>≠ FWM</td>
<td>buffer + timing</td>
<td>continuous</td>
<td>≠ FWM</td>
</tr>
</tbody>
</table>

Table 3.4: Overhead 3, for compatibility between the reactor and generator.

Continuous to continuous These types are very compatible to each other. A function can be transport, if the continuous flow rate has to be changed (slightly), dosing and a buffer are needed. The overhead can be avoided completely by integrating the reaction and generation functions. The continuous energy flow pattern from the reaction is taken over by the generator.

Reciprocal to reciprocal These transitions are equally simple as the continuous-continuous overhead, at least if the desired frequencies of the reaction and generation are the same. The reciprocal energy flow type has a shape and a frequency. If a frequency transition is desired, buffers and switching/timing is needed. It would increase the overhead while it is not likely to give benefits compared to the following method.

Continuous to reciprocal In this case the overhead consists of a timing/switching device that converts the potential energy flow from continuous to reciprocal. For the pressure and momentum engine the work is delivered by the reaction products, so the timing/switching has to be applied on the transport of reaction products. A more demanding component is needed for this function because it involves transport of gas and liquid under increased temperatures and/or pressures. In case of the heat engine, the timing/switching can be done by changing the heat conductance to or from the working fluid, which
Table 3.5: Summary of overhead 4: kinetic energy flow. Coupling between generator and FWM.

<table>
<thead>
<tr>
<th></th>
<th>generator output</th>
<th>overhead</th>
<th>FWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>#</td>
<td>shape</td>
<td>frequency</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>rotary</td>
<td>= FWM</td>
<td>linkage</td>
</tr>
<tr>
<td>2</td>
<td>reciprocal, linear</td>
<td>≠ FWM</td>
<td>gear + linkage</td>
</tr>
<tr>
<td>3</td>
<td>continuous, linear</td>
<td>≠ FWM</td>
<td>director</td>
</tr>
</tbody>
</table>

is simpler. A buffer and switching is likely to result in potential energy loss at this stage: heat, pressure or momentum.

**Reciprocal to continuous** This combination would require a buffer, it takes away the effect of timing/switching that is done before. It is not a desired situation for functionality is added while continuous reaction is beneficial easier by itself.

**Conclusion** In order to avoid losses and heavy components in between the reaction and generation, it is desirable to have as little as possible overhead between these functions. The transition involves the reacted but unconverted energy, thus losses in pressure, heat or momentum occur easily at this stage. The simplest option is integration whereby losses are minimized and the energy flow pattern of the generator is equal to that of the reactor. Transition of continuous to reciprocal energy flow might be desirable, for continuous reaction has benefits over cyclic reaction and a reciprocal generator is beneficial in terms of FWM compatibility.

### 3.5.4 Generation - FWM

The generation output types differ in three aspects: motion type, frequency and amplitude. The following procedure is used to attain successful coupling between generation and the FWM, the number of steps that is needed depends on the output of the generator.

1. Make frequency compatible
2. Convert to oscillating linear motion
3. Enable to the FWM amplitude

Five generation output types can be distinguished from the variables frequency and motion type. Table 3.5 displays the various coupling options. Overhead due to amplitude conversion is independent on these variation, it is discussed in 3.4.4.2. The overhead required due to the conversion of motion type and frequency is discussed below.

#### 3.5.4.1 Motion type and frequency

**Rotary + compatible frequency** A small overhead is required for this transition, for example a linkage system can provide the motion conversion from rotary to linear-reciprocating. The length and placement of the links helps to tune the amplitude. An important aspect of this conversion is that the rotary frequency must be really well synchronized with the FWM resonance frequency, also when small frequency changes occur. Two ideas could provide this: feed-back control or a slight higher frequency of the generator compared to the FWM, which causes a leading motion. These methods are not necessary easy and straightforward especially in combination with the amplitude variation. In the end, the FWM needs a certain net power input which the generator needs to deliver via the overhead. The possible damping by synchronization mismatch has to be taken into account.

**Rotary + deviating frequency** A deviating rotary frequency is easily converted to another frequency with a transmission. Considerations for rotary to linear conversion is given in the previous paragraph. A non-constant frequency of the rotary generator could be compensated with frequency control by the transmission, due to complexity, reliability and efficiency, this is probably not a feasible option.
Linear, reciprocal  + compatible frequency  This generator output is compatible to the FWM, no additional components are required.

Linear, reciprocal  + deviating frequency  A direction converting mechanism is required, a rectifier could convert the work in one direction, additional timing/control is required to redirect the work stroke. To the knowledge of the writer, it is difficult to achieve this in a simple reliable and efficient system. Frequency conversion via a rotary system is possible, but not very desirable.

Linear, continuous  + no frequency  Timing and switching is required to convert the work or force from linear-continuous to synchronized bi-directional. In case of the thruster generator, the flow can be switched between two oppositely oriented thrusters. Or the thruster is rotated or turned on and off. Some kind of buffer might be desired.

3.5.4.2 Amplitude

When the generator is loaded by the FWM above it’s power production, the amplitude decreases for a linear, reciprocating engine and the rotation frequency decreases for a rotary engine.

The required change in amplitude can be: making smaller, larger or just allowing for a variation. The amplitude-compatibility-step has to allow for the work stroke or cycle of the generator to be finished. The work has to be converted to the resonating FWM, at the positions, velocities and accelerations of the actuation locations. The FWM can operate at a certain amplitude range, so the actuator has to allow these changes to occur while the same power is delivered to the system.

3.6 Actuator concepts

Four concepts are compiled in this paragraph using the preceded functionalities and overhead. They are explained and evaluated.

3.6.1 Concepts

A number of promising principles were selected to build a various set of the four concepts.

1. Momentum thruster concept  The momentum process type gives the opportunity for the use of a thruster, which is a very simple and proven reactor-generator combination.

2. Fast rotary generation  Rotary motion type gives the opportunity of gears, thus a high frequency and hence a high power to weight ratio.

3. Continuous reactor  + reciprocal heat generation  The heat process type allows for easy combination of continuous reaction and reciprocal generation.

4. FWM compatible reaction and generation  Use of a reciprocal reactor and generator, gives the opportunity for synchronization/integration of reaction, generation and FWM.

   The concepts have with different characteristics and advantages, a scheme with a possible arrangement of energy flows and overhead is given in table 3.6. Overhead 1, storage and the overhead at 4 due to amplitude variation are not displayed, for they have similar elaboration options for the concepts.

3.6.2 Evaluation

The selected decision priorities from Section 3.2 give a direction for the solution. The displayed concepts are not evaluated separately because there is one design that is interesting and promising given the requirements that were listed. Arguments to choose for concept 4:

Power to weight ratio  Wageningen modelled different concepts using different thermodynamic processes. The calculations do not cover all the possible engines for these processes, but they give a general idea. The results displayed a feasible power to weight ratio for only the expansion engine. Losses will decrease the net power production, these have to be minimized in the concept.
<table>
<thead>
<tr>
<th>concept</th>
<th>overhead 2</th>
<th>reaction</th>
<th>overhead 3</th>
<th>generation</th>
<th>overhead 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>driving potential</td>
<td>continuous</td>
<td>momentum</td>
<td>linear</td>
<td>directionality</td>
</tr>
<tr>
<td></td>
<td>dosed rate</td>
<td></td>
<td>no f</td>
<td></td>
<td>timing</td>
</tr>
<tr>
<td>2</td>
<td>driving potential</td>
<td>continuous</td>
<td>pressure</td>
<td>rotary</td>
<td>gears</td>
</tr>
<tr>
<td></td>
<td>dosed rate</td>
<td></td>
<td>f (FWM)</td>
<td></td>
<td>links</td>
</tr>
<tr>
<td></td>
<td>active control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>driving potential</td>
<td>continuous</td>
<td>heat</td>
<td>linear</td>
<td>rectifier</td>
</tr>
<tr>
<td></td>
<td>dosed rate</td>
<td></td>
<td>f (FWM)</td>
<td></td>
<td>directionality</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>timing</td>
</tr>
<tr>
<td>4</td>
<td>driving potential</td>
<td>reciprocal</td>
<td>pressure</td>
<td>linear</td>
<td></td>
</tr>
<tr>
<td></td>
<td>dosed amount</td>
<td></td>
<td>f (FWM)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>timing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6: Four functional concepts.

**Efficiency** From theory and the Wageningen models it follows that for the momentum and heat engine there is a balance between efficiency and power to weight ratio. For the pressure engine, the efficiency and power to weight can be improved in parallel.

**Generator motion type** Rotary constructions allow for high frequency generation and hence a low generator weight. The calculations from Wageningen promised a sufficient power to weight for a linear reciprocal generator. A lot of - especially micro scale - problems can be avoided by using a linear reciprocal generator, and the amount of overhead can seriously be reduced.

**Simplicity / Compatibility** Compatibility of energy flows between reaction, generation and FWM offers the possibility of a very simple system and integration of functions. There is no additional weight, loss and possible failure from overhead components. Also the control of this system is likely to be simple and non-demanding. Simplicity improves the overall producibility and reliability. Timing and dosing takes place at the stage of 'internal energy', this involves only a fluid.

**Losses** Inherent problems of rotary constructions due to relative moving surfaces: friction, wear and leakage, can be avoided using a smart cyclic design.

An expansion engine using short term pressure peaks can decrease thermal losses because temperature increase is of a short duration.

There is no need for overhead between the reaction and generation stage, the loss of potential energy is minimized.

**Prepare for downscaling** Many of the micro scale problems can be avoided using this design. When scaling down, this concept remains interesting.

### 3.7 Conclusion

The pressure engine type is most promising in giving a beneficial balance between efficiency and power. Rotary generator type allows a higher power/weight ratio, but the power requirement is likely to be fulfilled with a pressure engine cycle. A very simple concept can be composed when it is chosen for a cyclic energy flow at the FWM frequency, throughout the actuator. A reciprocal generator can be integrated with a cyclic reactor, such that one can benefit from pressure peaks and short temperature peaks. Overhead is only required in between the storage and reactor function. The simplicity of this concept increases the chance for a reliable, producible and light device. The architecture of functions allows it to avoid or decrease micro scale problems as: leakage, friction and heat loss. It was tried to find the best actuator applied to the desires of the designed FWM, the choice may not be in general the best actuator. The proposal has the simplest execution of tasks, it allows for drastic integration which promises an actuator with great reliability and robustness.
Chapter 4

Working concept

The research as described in Chapter 3 was conducted to define the design space of the actuator. The functional representation of the MAV actuator by means of functions, made it possible to rate and make choices in certain design directions. A working concept is described in this chapter which allows for the actual development of the actuator in practice. The exact shapes and lay-out of the components - as displayed here - are not fixed. Chapter five and six delve deeper into the details of this working concept.

4.1 Working concept

The working concept is an example of the realisation of the previously determined functional components. The integrated working concept is explained together with the resulting characteristics.

4.1.1 Working principle

Figure 4.1 displays the working concept of the reciprocal actuator with the FWMAV compatible reaction and expansion function. This is a working concept, the specific components have to be developed further, the processes and energy flows of the concept are determined. It should be stressed that the current selection of components is a draft they are needed in order to provide the required functions.

In this concept, the functions of decomposition and expansion are integrated into one chamber. The fuel flows continuously to the reaction chamber through multiple channels driven by pressure in the tank. Droplets are formed at the ends of the channels which is the bottom of the reaction/expansion chamber. A piston - which is covered by catalyst material - is coupled to the reciprocal motion of the FWMAV. When the expander is at minimum volume, the reaction starts with the piston surface touching the accumulated fuel. Then the work stroke takes places, expanding the reacted gas. A spring-like structure is placed between the FWMAV and the piston, such that the decomposition takes place over a range of amplitudes of the FWMAV. The following list provides the preliminary functions and components.

Storage - Closed fuel tank

Figure 4.1: Schematic drawing of working concept
• Fuel filling via a valve.
• Pressurized using initial pressure.

Transport - Multiple thin channels
• Fuel is driven by pressure in tank.
• Flow is limited by viscous friction.
• Fuel accumulates at the bottom of the reactor in droplets due to surface tension.

Generation - Expansion with a membrane piston
• Volume increase is allowed by a sealed piston-cylinder construction, similar to a membrane.

Exhaust - Membrane opening/closing
• The decomposed gases are allowed to pass through holes inside the piston.
• When the piston moves to near outer position, the seal moves away from holes at the sides of the piston, such that the gases escape.
• When the piston returns to its inner position, the exhaust holes close at a later moment because the seal bends in a different way. Compression can take place.

4.1.2 Characteristics
A characterisation of the working concept is given. There are properties that follow from the general concept, and properties that follow from this specific execution of functions. The combination of these properties should convince of this concept

4.1.2.1 Advantages
Simplicity and integration
• The reaction and expansion chamber are integrated.
• The piston combines functions of expansion, reaction and exhaust.
• No transport or retention of hot, pressurised, multi-phase substance is needed.

Control
• No active control components are required:
  − The timing of the reaction, expansion and exhaust is determined by the FWMAV position and motion (simple feed-forward control).
  − Fuel rate input is determined by pressure in tank.
  − Control of dosage and reaction is separated.
• The system can be started manually by exciting the system to the reaction amplitude.
• Control components could be added to increase efficiency and/or flexibility.

Efficiency
• Reaction occurs when the expansion chamber is at a minimum volume, so the obtained pressure is maximal.
• Full expansion of the reaction products is possible.
• The duration of the repeating reactions is short, pressure peaks can be used in the expansion.
• There is little work required for fuel or gas transport.
4.1.2.2 Disadvantages

- A continuous reactor is not used, while at micro scale, it is a quite robust and proven technique. (e.g. MEMS thrusters)
- All the reaction products, gas as well as liquid ends up in the reaction/expansion chamber and are possibly difficult to get rid of.
- Fabrication of a multifunctional piston can be challenging.
- Start and stop of the fuel flow is performed by increasing and decreasing the pressure in the tank. This has to be performed manually, or additional systems are required.

Conclusion This is a very simple concept, in which all of the required functions are included. The choice of components might not be optimal, but the concept shows a combination of components that could work. The start of reaction, expansion and hence work generation and delivery is started by the FWMAV position. It is a guarantee for good timing of work transmission. The concept has the potential to be efficient. Because of integration of functions, the actuator is simple and therefore it has a great chance of success for a producible and robust design at micro scale.

4.2 Components

In order to get the most out of the concept, every part of the actuator needs to be examined in detail. When making a choice, not only the working principle should be examined but also arguments like production, weight, robustness etc. Some of the components will be discussed in detail in this research, they will be selected using critical functions of the concept.

4.3 Critical functions

In order to examine different parts of the actuator separately, critical actuator functions are defined. All necessary actions for work production have to be involved in this list. The expected challenges are listed in Appendix B. The list is used to find the most important and challenging parts of the concept, these will be developed first.

1. Refuelling Refuelling is the supplying of new hydrogen peroxide fuel to the storage facility. The storage requires an inlet which can be closed, such that the volume can be pressurized.

2. Fuel transport A certain average flow rate of fuel is required such that the right amount of internal energy is transported to the reaction/expansion chamber. A driving force is involved with some kind of control.

3. Fuel accumulation Fuel is repeatedly accumulated at a confined area, such that it can be reached by the piston with catalyst material. Leakage of fuel to unwanted areas must be avoided.

4. Reaction execution Fuel has to be (absorbed and) decomposed within half the time of the resonating frequency. The decomposition efficiency has to be as high as possible, the catalytic reaction has to be reliable for a great number of reactions.

5. Reaction timing Depending on the rate of fuel absorption and reaction, a certain contact time between catalyst material and accumulated fuel is required. Also for the timing of work generation, there has to be a correct start and stop of the reaction. Duration of contact can be controlled actively.

6. Expansion A body that performs conversion of pressure to work by gas expansion is required. This is performed by a closable, variable volume that expands in one direction. The volume should have inlets and outlets for fuel entry and exhaust discharging. Deformation resistance of the volume should be small, or the deformation energy should be able to be stored and released. Thermal insulating the volume is beneficial.
7. **Exhaust** An exhaust valve should be opened and closed in a way that the maximum amount of work is produced by the pressurized gas. Full expansion of the gas is desired but under-pressure should be avoided.

8. **Suspension** Suspension couples the actuator to the FWMAV in such a way that work can be transferred to the FWMAV. Meanwhile the FWMAV should be free to move in its eigenfrequency. The suspension should allow the actuator to operate and provide work at a range of amplitudes. This can be a part of the suspension or the actuators internal structure.

**Priority**

Fuel delivery combined with fuel accumulation is very essential for the working and reliability of the actuator. It will be the first critical function or subsystem to be examined. During the process of developing components, the following approach is used:

1. develop a concept and estimate whether it is feasible
2. integrate components in an early stage for examining of combined working
Chapter 5

Critical component I - Fuel delivery

In this chapter the critical component ‘fuel delivery’ is discussed. It includes the fuel transport from the storage chamber to the reaction site and the fuel accumulation in the reaction/decomposition chamber. The different aspects of fuel delivery are explained, a fuel driving method is selected and researched. Models and experiments are used to test some preliminary fuel delivery systems.

5.1 Introduction

The fuel delivery system has to transport a certain rate of fuel to the reaction/expansion chamber, such that at each cycle the right amount of energy is available. Fuel is repeatedly accumulated in a confined space where it can be reached by the ‘piston’ with catalyst material. The following tasks have to be performed:

- gateway from storage to reaction/expansion chamber
- driving force
- flow rate control
- fuel accumulation, confined but reachable
- (long term flow stop and back-flow resistance)

A gateway is formed by one or multiple channels, which can be dimensioned in such a way that the desired amount of flow rate is provided. The control that is required is possibly provided by the driving force. The control aspect is treated first.

5.2 Control

5.2.1 Accuracy of flow control

The control required depends on the demands for the fuel flow, three levels of accuracy are distinguished:

Passive steady flow control A certain minimum constant fuel rate is supplied. It depends on the power requirement of the MAV as a function of mass and the efficiency of the generator, transmission and reaction. In the case that hydrogen peroxide is used with a concentration of 35 \%_{wt} and the overall engine conversion efficiency is 1 \%, the required fuel for a cycle is 1.6 \mu l. This is a rate of 44 \mu l/s. When the fuel concentration is increased to 95 \%_{wt}, only 0.5 \mu l is required, an additional increase of the efficiency to 5 \% results in a fuel use of 0.1 \mu l per cycle.

Feed forward controlled decreasing flow This rate decreases during flight, because the mass of the system decreases. The total fuel consumption weighs up to half of the systems entire mass.
Feedback controlled flow  Perhaps, control of the rate is desired during operation. Certain movements might require more power than others and when dealing with payloads the power input demand can change. Active control is not necessary, for The FWMAV needs a quite constant input and the maximum required FWMAV input can be the minimum actuator output. The over production is probably dissipated in the system without causing a problem, but it is almost constant source of loss. More control will increase the efficiency and flexibility of the system, as the power production can be adapted to the current need. Feed forward control can be used for the long term decreasing flow, feedback control enables instant fuel flow changes, adapted to the current need.

5.2.2 Components

Table 5.1 shows how a liquid can be controlled when flowing through certain components. The second column shows what possible outputs are, the third column shows how the flow is influenced by an external driving force. When a pump is used for control, there is no external driving force required. In the other cases, the external driving force is required and limits or determines the rate of the fuel flow.

Two other control components might be required.

1. Due to the reaction, the pressure in the fuel delivery system increases temporarily, but suddenly. When the means of flow control is too weak, an extra component is required to oppose this pressure peak.

2. If a pause of flight is desired and the chosen flow control device cannot provide this, a component can be added to do so.

5.3 Fuel driving methods

Table 5.2 shows what methods or phenomena can be used as a driver for fuel flow. The upper methods are 'internally' driven which means that properties of the fuel itself enable the driving forces and determine the magnitude (or at least partially). The external methods are imposed externally, therefore they are intrinsically more controllable. The parameters that determine the magnitudes of the phenomena are divided into categories, which shows to what extent the driving force can be controlled. Some methods are controlled mainly during operation, others a mainly determined by the design (and production). Methods with uncontrolled parameters are difficult to use, except for when the values can be predicted. Constant parameters are known or can be determined.
**Pumps** Pumps are available in all kinds of sorts and sizes. Most pumps are driven by electric power or mechanical input. The benefit of pumps is that they can drive as well as control a certain flow rate or dose. This could be a convenient integration of tasks. Disadvantages of pumps are that external power is required and that, compared to internal driven methods, they involve more components and complexity. Flow driven by an electric field has similar advantages and disadvantages as the electric pump, furthermore, the fuel needs to carry charged particles.

**Pressure driven** The storage can be pressurized initially, for instance by using a gas, a spring or a stretchable container. Another possibility is pressurizing the fuel in a confined volume by a small amount of catalyst. Both have a specific pressure profile as a function of time or volume. This can be used to implement feed-forward control by design. A disadvantage is that control of the pressure or flow during flight can be done only by added components. Fuel flow goes on from the moment that the pressure is increased or is increasing.

**Internal driven flow** The first four driving methods are phenomena that are naturally present on the fuel in the actuator, using one of these methods could result in a very simple system. The methods have no parameters that can actively control the magnitude during operation. Further all of these methods include uncontrolled parameters and some parameters can be controlled during the design phase.

**Suggestion** When we focus on providing steady flow of fuel, there is one very interesting driving method that could allow for a very simple system. Surface tension is present at the scale of the MAV actuator, it can dominate the mass sized forces: gravity and acceleration at certain small dimensions. The magnitude and direction of the forces related to surface tension are a function of material properties, contact shape and temperature. It reaches an equilibrium as a result of shape and gravity (and acceleration). A steady amount of fuel is required at a certain location in every cycle. It would be really nice if the equilibrium position of the fuel could provide this amount. The flow and position of the fuel are a function of all forces acting on it, but it should be dominated by surface tension forces.

### 5.4 Surface tension

Surface tension is studied in this section to get a better understanding of the phenomena. Theory, models, measurements and experiments are used to explore the applicability of the phenomenon for the Atalanta actuator. Some related effects to surface tension are: droplet forming, capillary action, capillary angle, solubility/non-solubility and hydro-phobic/philic surfaces.

#### 5.4.1 Surface tension theory

**Introduction** Surface tension is the elastic tendency of liquids which makes it acquire the least surface area possible. (Fig. 5.1a) At liquid-air interfaces, surface tension results from the greater attraction of water molecules to each other (due to cohesion) than to the molecules in the air (due to adhesion). The net effect is an inward force at its surface that causes water to behave as if its surface were covered with a stretched elastic membrane. Because of the relatively high attraction of water molecules to each other, water has a high surface tension compared to that of most other liquids. Surface tension is an important factor in the phenomenon of capillarity. Surface tension [N/m] is equivalent to surface energy [E/m²], which is a more general term in the sense that it applies also to solids and not just liquids [58].

The shape of droplet is the result of surface tension. When a droplet is in contact with a solid, its shape is determined by the properties of the three substances that are present. The Young-Dupre relation:

\[
\sigma_{AB} + \sigma_{BC} \cos \theta = \sigma_{AC},
\]  

relates the contact angle to the surface energies of each couple of materials (Fig. 5.1b). \( \theta \) is the angle between the solid wall and the intersection between the two-fluid interface. The three sigma's represent the surface energies. The contact angle is measured within the densest fluid. Table 5.3 shows the contact angles for water in air on different solids. When solids have a strong affinity with water (\( \theta << 90^\circ \)), they are called hydrophilic. If the surface repels water strongly (\( \theta >> 90^\circ \)), it is called hydrophobic.
(a) Forces on molecules in a liquid and on the interface with a gas. (b) Young’s Equation: relation between surface tension and contact angle. (c) Unequal height distribution of fluid in open tubes due to capillary action.

Figure 5.1: Surface tension illustrations.

<table>
<thead>
<tr>
<th>Droplet dispersion</th>
<th>$\theta$</th>
<th>Materials at interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-wetting</td>
<td>&gt; 90°</td>
<td>water + air + most plastics</td>
</tr>
<tr>
<td>Wetting</td>
<td>&lt; 90°</td>
<td>water + air + most metals or glasses</td>
</tr>
<tr>
<td>Perfectly wetting</td>
<td>0°</td>
<td>liquid helium on most solids</td>
</tr>
</tbody>
</table>

Table 5.3: Contact angles for water in air on various solids.

**Capillary action**  Capillary action is the ability of a liquid to flow in narrow spaces without the assistance of, and in opposition to, external forces like gravity [55]. The effect is shown in Figure 5.1c for a red fluid in open glass tubes of various diameters.

The height $h$ of a liquid column is given by:

$$ h = \frac{2 \gamma \cos(\theta)}{\rho g r}, \quad (5.2) $$

where $\gamma$ is the liquid-air surface tension, $\theta$ is the contact angle, $\rho$ is the density of the liquid, $g$ is the acceleration due to gravity, and $r$ is the radius of the tube [55].

More general, the pressure difference across an interface due to capillary action are is given by the Young-Laplace equation:

$$ p_c = \frac{2 \gamma \cos(\theta)}{r} \quad (5.3) $$

The equation is only valid under capillary equilibrium.

**Marangoni flow**  When the value of surface tension varies along an interface, the corresponding stress also induces liquid motion. Marangoni flows are driven by such surface tension gradients. In general, surface tension depends on the temperature and chemical composition at the interface. Consequently, Marangoni flows may be generated by gradients in either temperature, chemical concentration or electrical potential at an interface. The Marangoni effect:

$$ \nabla \sigma = \frac{d\sigma}{dT} \nabla T + \frac{d\sigma}{dc} \nabla C + \frac{d\sigma}{dV} \nabla V, \quad (5.4) $$

describes the gradient of surface tension as a function of the gradients of temperature, concentration and electrical potential and the surface tension dependency on these. There cannot be a static system in the presence of surface tension gradients [9, 4].

**5.4.2 Contact angle measurements**

Measurements are performed to obtain the contact angles of hydrogen peroxide on different solids in air. The angle gives a practical estimation of the surface tension and the magnitude of the capillary effect. It is used later to make a model.
5.4.2.1 Background

"When the models are verified with experimental results, the data has often poor reproducibility apart from those where surfaces where ultra-clean and polished to roughness less than a nanometre" [9]. The real static contact angle depends on:

- The chemical composition of the surface: metal micro structure and absorbed molecules.
- Roughness of the solid surface.
- Characteristic angle at which the contact angle value is measured.

Capillary angles and surface energies could be obtained from tabular data, but the values for surface energy of hydrogen peroxide with many solids is difficult to find. Further, some practical values come in handy for the conditions of the liquid if the fuel delivery system are not as perfect as during well controlled measurements.

5.4.2.2 Method

The tested materials were Aluminium, PMMA and polycarbonate. Small plates were cut and cleaned with acetone. The measurements were performed in a clean room. The samples were placed flat on table calibrated with a spirit level, with a HD/HS camera viewing from the side. An Eppendorf pipette was used to deposit the droplets. Two liquids were applied on the plates materials: distilled water and 35% wt hydrogen peroxide from Sichma Aldrich. A series of photo’s was taken directly after deposition. The contact angles were measured at both sides of the droplets.

5.4.2.3 Results

Figure 5.2 shows the averaged angles that were measured for the different combinations of solids and liquids. (Appendix C.2 for a photograph and verification)

5.4.3 Capillary flow model

5.4.3.1 Model

An analytical model is made that gives an approximation of the fluid flow inside a tube suspended in a circular bath of liquid (Fig. 5.3a). The model is used to estimate the fuel flow rates of the fluid, to estimate the recovery time of the fuel level after absorption by the decomposition unit. The model is based on the equilibrium of forces acting on the fluid in the tube: gravity, capillary, acceleration, and viscosity. It is assumed that fluid flows from or to a ‘large’ reservoir into multiple identical small tubes, the flow inside each of the tubes is assumed to be the same. The flow inside one tube is modelled. The capillary force is assumed to be constant, it is derived using the Young-Laplace Equation 5.3. It is an approximation, as the equation is only valid in a static fluid situation. But for a rough approximation of fluid flow rates, the complex subject of dynamic contact angles was not researched. The amount of liquid in the capillary was assumed constant for the derivation of the viscous and inertia forces, such that an second order differential equation was obtained. Other details on the model are explained in Appendix C.1.
5.4.3.2 Results

**Static fuel height in capillary** The static fluid heights for 35% \( \text{wt} \) HP in capillaries with a range of diameters, is given in Graph 5.3b. The measured capillary angles were used to derive the results. The result shows that the differences in capillary angles of the materials cause large deviations. A 1 mm diameter tube gives a static height of about 14 mm for the acrylic (PMMA) tube, while the fuel in an aluminium tube stays below 1 mm.

**Transient liquid response** The results displayed here are for 35% \( \text{wt} \) HP in a PMMA tube (measurement results are used). The capillary length is 10 mm, the storage has a diameter of 10 mm and contains 1 gram of fuel.

Typical behaviour of a second order model was observed for the liquid height of the fuel in the tube. The liquid height rises or descends to its equilibrium position, with some oscillations or with a damped curve. Figure 5.3 shows transient responses of fuel in tubes of various sizes. The height at which the flow starts is a function of the tube diameter and the number of tubes, the volume that is displaced in each situation is 1.6 µl. The displacement is achieved when the meniscus reaches 'height end of tube'. The flow continues to its equilibrium position (not shown), as if the capillary has an infinite length. The two graphs display quite different rise times: the point at which the meniscus reaches the end of the tube. Most of the rise times on the left graph are approximately 30 ms, the 1 mm capillary is the fastest, showing the optimum of the series. The right graph shows rise times of about 5 ms, this is accomplished because the required fuel flow is distributed over multiple tubes and the resistance in each tube is decreased, because the length is shorter.

5.4.3.3 General model conclusions

The model predicts that capillary action can provide sufficiently fast flow, to serve as a driving mechanism for the cyclic fuel delivery. The choice of material, the number of tubes, the diameter and length are
important to obtain the required response. The model results are an approximation, for the dynamic contact angle is not taken into account. Also the assumptions and inaccurate boundary conditions cause errors. But probably practical factors as temperature and contamination influence the results in an even greater respect.

5.4.4 Simple capillary experiments

Experiments were done to investigate some effects of capillary action. Channels, reservoirs and openings were designed in 2-D, which were laser cut in PMMA. Each device consisted of three layers that were glued together. The internal channels were tested with water. Some test results, drawings and figures can be found in Appendix C.3.

Conclusion

- The water flow achieved in the experiment, shows that capillary action is likely to provide the right flow speed to be able to function as a fuel driver for the MAV actuator.
- Measurements showed that even faster flow motions can be expected for hydrogen peroxide (solution) compared to the tested water.
- Capillary force at this scale can dominate over gravity and accelerations for the tested combination of substances: water, PMMA and air.

5.5 Fuel delivery concepts

Based on the knowledge gained in the theory, model and experiments, some concepts are made that can provide fuel delivery. The concepts provide fuel flow and accumulation, they work mainly by means of capillary action. The feasibility for application of the capillary fuel delivery system (CFDS) are examined using the model (5.5.2) and new experiments (5.5.3).

5.5.1 Working principle

The working concept (Chapter 4) provides a basis for the placement of the CFDS. The CFDS provides flow from the storage to the reaction/expansion chamber, fuel has to accumulate at a side of this chamber such that it is approachable for the 'decomposition unit'. This unit is connected to the FWMAV, it moves along with the body its resonance. The movement of the unit, to and away from the fuel accumulation side, provides two functions:

1. on and off switching of the reaction or exchange of fuel and
2. the increase and decrease of volume such that expansion is accomplished in a cycle.

The volume change can be achieved in many ways, in the proposed CFDS concepts a 'membrane piston' set-up is drawn. Six CFDS concepts are presented (Fig. 5.4, the inlets of the transport system is suspended in a storage tank. The fuel systems provide flow and accumulation or injection of the fuel at the bottom of the reaction/expansion chamber.

1. Pin-Tube Due to capillary action, tubes fill themselves entirely with fuel, to achieve this, the tubes need a sufficiently small diameter. Needles on the decomposition unit penetrate the tubes to acquire fuel for the reaction. The needles can be covered with catalyst or the needles displace the fuel such that it reacts elsewhere.

2. Conical hole Small channels lead to conical holes at the bottom of the reaction chamber. The transition from the channel to open structure is smooth, this should aid the fuel to pass the corner of the cone, such that it is partially filled, by means of capillary action. Oppositely shaped cone structures are attached to the decomposition unit, again covered by catalyst to start the reaction or to allow displacement of the fuel. Further the conical shapes aid the alignment of the decomposition unit.
3. **Surface droplet** Tiny channels gradually open up when approaching to the surface. Due to capillary action the channel is filled and the liquid creeps up the sides of the opening channel to form a droplet above the opening channel. A plate covered with catalyst approaches the surface and touches the droplets. For this design it is important that the liquid rises above the chamber surface.

4. **Hydrophilic surface** The bottom of the reaction chamber is made hydrophilic, it should allow the fuel to flow from the channels onto the surface. The channels are filled due to capillary action, small rounding at the end of the channel help the fluid to exit the tube.

5. **Grooves** Horizontal channels or grooves are situated at the bottom of the reaction chamber. Thin, vertical channels provide flow to the channels by capillary action. The grooves are narrow and shallow such that they are filled with a layer of fuel. A certain shape might be needed to make the transition between the vertical and horizontal surfaces, such that the fuel continues to flow. Features on the decomposition must allow for flow or direct reaction of fuel.

6. **Capillary auto-ejection** Capillary auto-ejection is achieved by [40, 60], it is demonstrated in a film [33]. A channel that ends in a nozzle, fills itself with liquid and ejects droplets, driven by capillary action. In this concept, the droplets collide on the catalyst surface. The channels have to be (partially) empty before ejection can occur again. This can be done for example with the reaction pressure or it can be achieved with compression.

### 5.5.2 Model evaluations

The feasibility of the concepts is predicted using the variations on the model and theory. The CFDS has to deliver 1.6 µl within 18.5 ms. The conclusions are displayed here, explanations of model variations and more details can be found in Appendix C.4.

**Concept 1 - Straight holes** For a single PMMA tube of 2 mm diameter and 5 mm length, the modelled rise time is 13 ms. The extracted fluid amount results in a liquid level change of about 0.5 mm,
that is is the approximate distance the pin has to penetrate into the channel. As for sizes, dimensions and response time this concept seems feasible.

Concept 2 - Conical hole Due to the angle of the conical hole, the vertical force component of the capillary force is decreased, also as the liquid rises, the mass of the liquid in the cone increases disproportional. The angle of the cone is limited by the contact angle, when the sum of the two angles is larger than 90°, the surface tension provides no force component upwards. Thus limiting the cone angle for PMMA to below 30°. Some calculation are done to examine the equilibrium position of the liquid in a cone, the cone is preceded by a straight tube section. For a cone angle of 20°, a straight tube of 1 mm diameter and 5 mm length, the height in the cone is 3.2 mm. In case of a cone angle of 25°, a tube of 2 mm length, the height is 2.1 mm. Volumes in the cones are 44 µl and 20 µl respectively, that is above the volume needed in a cycle, but nothing is said about the recovery time.

Concept 5 - Grooves The height of the fuel in the grooves is approximated assuming square edges of the trench and groove length that is much larger than the width. The result shows that the height scales linearly with the groove width. For a width of 2 mm, the height is 3.3 mm, the required liquid volume per stroke is easily met. The system is likely to have sufficient re-flow times, for the equilibrium height that was calculated lies much above the required depth. Alignment of the decomposition unit: the translation and rotation, are important in this concept.

Concept 6 - Capillary auto-ejection Under the earth’s gravity condition experiments were carried out with acrylic tubes [40, 60]. The tubes had a length of 5 mm an inner diameter of 1.5 mm, auto-ejected (probably water) droplets had a volume of about 0.2 µl. Applying this system would require eight tubes to obtain the fuel amount of 1.6 µl for a stroke. Rise plus ejection of the liquid took about 15 ms, which is about the duration of a cycle. A small calculation showed that the power required to overcome the capillary force of 8 tubes is less than 1 mW (derived with static contact angle).

Conclusion It is expected that difficulties due changing boundary conditions can be overcome. Forces due to accelerations and rotations can be dominated by the capillary force. If during operation the fuel storage level changes strongly, its effect can be decreased by for instance applying a sponge like material on the inside of the storage.

5.5.3 Experiments
5.5.3.1 Fabrication
Four plates with a series of holes were made in 4 mm PMMA plate, to represent the concepts 1, 2 and 3 (Figure 5.5a). Holes for concept 1 were made with drills with diameters in between 0.4 to 1.2 mm and diameters of 0.5 and 1.5 mm using laser cutting. The drills used for the other concepts had diameters in between 0.75 mm and 2.3 mm. Cutting oil was used during drilling, the holes were cleaned using soap and water. The hydrophilic surface concept was tested using a PMMA plate with holes, made by laser cutting. The plate was treated for 3 minutes in a plasma oven under 0.22 bar pressure with oxygen or hydrogen gas.

5.5.3.2 Method
The samples were placed in a basin such, that the holes oriented vertically and the sides were visible. The basin was filled with distilled water, the flow in the channels was recorded with a high speed camera from the moment the water touched the underside of the sample. The water in the holes was blown away with an air gun and the experiment was repeated.

5.5.3.3 Results
General After fabrication the shape and surface quality of the channels looked fine. Observations of the video images revealed that the inner surface of the drilled channels were very uneven, see figure 5.5b. Lots of features in the order of 10 µm to 100 µm were visible. This is expected to be the main cause for the sudden and uneven fluid flow motions that were observed. Almost none of the drilled holes filled
Table 5.4: Water rise height and flow rate for drilled and lasered holes in PMMA. Rate is the average flow rate over the displayed distance.

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>Rise height [mm]</th>
<th>Rate [µl/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 (drill)</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td>0.6 (drill)</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>0.4 (drill)</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>1.5 (laser)</td>
<td>1/2/3</td>
<td>0.9/0.7/0.6</td>
</tr>
<tr>
<td>0.5 (laser)</td>
<td>2.6</td>
<td>92</td>
</tr>
</tbody>
</table>

Concept 1 - Straight holes  Very rapid and sudden fluid flow motions were observed in the drilled straight tubes. In none of the cases the channel filled itself at once, often the channels were not filled completely. Results of some of the fastest observed fluid flow rates are shown in the table 5.4. The flow in the lasered holes was much more steady and the fluid often reached the top. In the 0.5 mm lasered tube a very high fluid motion of 2.6 mm in 50 ms was reached. The repeatability of the capillary action in the laser holes is better than that of the drilled holes.

Concept 2 - Conical hole  There was barely any flow observed in the conical shaped holes. One of the holes had a sloped wall from the bottom, it gave some upward fluid flow (figure 5.5bb). Other holes started with a straight hole than became conical shaped, the transition was rough, the fluid remained in the straight section.

Concept 3 - Surface droplet  The inner surface roughness problems prevented the liquid from steady flowing upwards. Figure 5.5bc shows the best finite result, an experiment in which the liquid came almost half way the tube, it travelled partly through an area with increasing diameter.

Concept 4 - Hydrophilic surface  A droplet deposited on the treated PMMA sample gave an angle of approximately 80°, clearly the surface became more hydrophilic. The effect was similar for the plasmas from oxygen and hydrogen. The flow test showed that the channels were filled with water due to capillary action, but the upper surface was not wetted due to the extra attraction.

Concept 6 - Capillary auto-ejection  Attempts to repeat the performed experiments failed, the inner surface was too rough to provide a steady upward flow.
5.5.4 Conclusion

The upward fluid flow rate achieved in straight channels was proven to be sufficient for providing fuel flow for the actuator concept. A flow rate of 94 µl/s was achieved in a tube diameter of 0.9 mm, while 44 µl/s is the required flow rate. The channel was lasered in PMMA, lasering provided quite steady and reliable flow compared to drilled holes. Tests of the concepts 2 and 3 did not succeed due to the fabrication quality, concept 4 did not show the desired response.

Capillarity driven auto-ejection is able to provide liquid sufficiently fast, but repeating the ejections will be challenging as the fluid has to be pushed back in the channel equally, with the right volume and the right timing. It makes this concept more complex and thus less favourable than the capillarity driven fuel accumulation methods.

The material and surface quality is very important to obtain fast and predictable capillary flow. Laser cutting gives a sufficient surface quality, but it is limited to 2-D shapes and the minimum size is limited by the laser spot size.

5.6 Conclusions

Capillary action is a very interesting phenomenon to provide fuel transport and accumulation at the reaction site. Capillary action brings a fluid that is in contact with another fluid and a solid surface, in equilibrium position. In theory it can repeatedly provide a constant fuel amount, by restoring the equilibrium position of the liquid at a designed location. The liquid flow is fast enough to provide fuel in the actuator when the channels are in the order of 1 mm, further it can provide a force to oppose gravity and accelerations.

Further research is needed to find a better performing fuel delivery device, aspects of the represented concepts can be combined to obtain the desired combination of flow speed, accessibility of the fuel and reliability. The fabrication has to be improved for testing these concepts, in parallel a material with appropriate properties has to be found, PMMA cannot stand a work temperature above 80 °C.

When a CFDS is integrated in the actuator, other aspects will influence its performance. Surface tension is influenced by temperature and concentration. Acceleration, reaction and compression pressure act on the fluid, also the amount and position of the liquid in the storage tank changes. Some of these can be predicted, dominated or designed for. In the end, control of the exchanged fuel amount is desired in order to increase robustness and efficiency. Methods could be the application of: valves, an electric field or position control of the decomposition unit.

The predictions and experiments showed that accumulation of fuel is no problem. The complexity increases a lot, when the fuel has to be extracted. Therefore it is chosen to examine the fuel delivery function further in combination with fuel extraction. Chapter 7.
Chapter 6

Critical component II - Reaction

The fabrication and understanding of a catalyst material is a subject on its own. As well as when the process is transferred from Macro- to Microscale and again when switched from continuous to batch reaction. Based on Chapter 3 and 4 in which the reciprocal linear actuator was chosen, a catalyst has been searched that can provide repeated batch decomposition of hydrogen peroxide (HP). Starting at the point where A. Meskers stopped his catalytic production and experiments, the following has been tried: finding a suitable and light weight support for the catalyst, developing a durable catalyst layer and obtaining reaction speeds sufficient to support the actuator concept.

6.1 Introduction

6.1.1 Batched decomposition

Batch decomposition testing  As previously discussed in Chapter 1, A. Meskers fabricated catalytic material according to the method of Kapteijn et al. [28], to test the decomposition of hydrogen peroxide droplets. The execution of catalytic batch reactions is not common and not well researched yet. The best results were obtained by a catalyst fabricated from a Manganese Acetate precursor [41]. The average achieved reaction time was 150 ms for a droplet of 22 µl 30 %wt, the reaction time is not sufficient yet for the actuator, but the required droplet volume is lower. The obtained reaction rate of 0.161 g/s is sufficient for the actuator's energy need. The Manganese Nitrate precursor showed an average reaction rate of 0.0201 g/s, which is below the desired rate. The catalyst samples deteriorated quickly during the first reactions, the main cause was the unevaporated water that occupied the catalytic surface after reaction, also some catalytic material tended to detach from the samples. The catalyst was fabricated on ceramic tiles with an intermediate porous layer. The fabrication involved multiple spin coating and coating steps and three temperature treatments of longer than 8 hours.

Hydrogen peroxide decomposition  The decomposition of hydrogen peroxide:

\[ \text{H}_2\text{O}_2(aq) \rightarrow \text{H}_2\text{O}(l) + \frac{1}{2}\text{O}_2(g), \]  

delivers 98 kJ/mol of energy. Up to now, hydrogen peroxide was used in diluted form. The reaction energy is used to heat up the reaction products and to partially evaporate the water that is present. Starting at room temperature, complete evaporation of the water needs a hydrogen peroxide concentration of approximately 70 %wt.

6.1.2 Goal

This chapter describes the search for a catalyst that is fitted for the actuator concept. The following steps are taken:

- Try to understand the catalytic decomposition and predict what reaction time can be expected for droplets of HP as a function of:
  - droplet size
• Find an appropriate material or method to provide the support for the catalyst in the actuator.
• Develop the fabrication process of catalyst as such, that reliable cohesion and adhesion is obtained.
• Test the catalyst with fuel volume sizes that correspond to the fuel volume that is needed in one actuator cycle.
• Try to obtain sufficient and maximum decomposition times.

Quantitative The desired reaction parameters are given in table 6.1. Sufficient decomposition time is described as half the time of a 27 Hz cycle of the actuator. The energy that needs to be decomposed, is derived with: the FWMAV power need (0.5 W, Section 1.3.3), the frequency, the decomposition energy and the overall conversion efficiency, taken as 1%. The fuel amount per cycle follows from the fuel concentration, for safety reasons it was chosen to perform the experiments with a medium concentration of hydrogen peroxide: 35 %wt. The catalyst material needs to endure for several minutes of operating time in the end, to test the concept a durability of approximately 100 cycles is sufficient.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction time</td>
<td>18.5</td>
<td>ms</td>
</tr>
<tr>
<td>Average reaction rate</td>
<td>0.03</td>
<td>g/s</td>
</tr>
<tr>
<td>Expected decomposition per flight</td>
<td>8100</td>
<td></td>
</tr>
<tr>
<td>Fuel for one cycle (1 %eff, 35 %wt)</td>
<td>1.62</td>
<td>µl</td>
</tr>
<tr>
<td>Fuel for one cycle (5 %eff, 35 %wt)</td>
<td>0.32</td>
<td>µl</td>
</tr>
<tr>
<td>Fuel for one cycle (5 %eff, 95 %wt)</td>
<td>0.10</td>
<td>µl</td>
</tr>
</tbody>
</table>

Table 6.1: Desired reaction parameters for a single cycle reaction of 35 %wt hydrogen peroxide, in case of a 1% total conversion efficiency.

6.2 Catalyses theory

More extensive explanation of the theory used is displayed in Appendix D.1. According to Do et al. [15] the heterogeneous reaction of hydrogen peroxide on a solid catalyst can be modelled with a second order reaction. The rate constant is given by the Arrhenius relation, for a single rate-limited thermally activated process.

6.3 Model

Introduction A model is used to get an estimation of the achievable reaction time for a reaction with smaller droplets and for reactions with droplets of a higher hydrogen peroxide concentration. A transient iterative model is built that simulates the catalytic decomposition of hydrogen peroxide. The catalyst concentration is assumed to be constant during the decomposition, which reduces the model to first order. A rough method is used to include the droplet size in the model: The fuel droplet that approaches the catalyst is assumed to be spherical, which allows for the derivation of a surface area to volume ratio. A change in droplet size is - by this ratio - directly related to the catalyst concentration: the concentration increases as the droplet size decreases. Parameters for the model are based on measurement results of Meskers and other literature. Derivations and further explanation can be found in Appendix D.2.

Results

1.6 µl droplet of 35 %wt concentration HP Figure 6.1 shows graphical results of the model for a 1.6 µl droplet of 35 %wt concentration HP. The red vertical line shows the point at which 99% conversion of the HP is achieved, it is in 15 ms, within the required time. It can be observed in different graphs that the reaction accelerates itself, as time elapses. Temperature increase causes the rate constant to increase which accelerates the temperature increase again: it is a positive feedback system until all HP
has decomposed. Once boil temperature is reached, the reaction rate is high and the fuel is decomposed very quickly. The dissipated energy evaporates the water that is present - the increase in quality - the present water amount increases from 2.2 µg to 2.8 µg during the reaction. The energy decomposition rate decreases as the HP concentration lowers at the end of the reaction.

Energy decomposed for different droplets  The trends in Figure 6.2 show the trend in energy decomposition for various droplets. The two lines for a 1% efficient engine end up at the same energy level, also for the lines of the 5% efficient engine. The first line displays the reaction that is currently desired for each actuator stroke, the details were given in the previous figure. A decrease in droplet size results in a faster reaction: the second line. All droplets with a higher concentration decompose much faster, for the reaction is started up much quicker.

Conclusions  The model gives a transient decomposition response that uses a changing, temperature dependent, rate constant. It shows a fast increasing reaction rate as the temperature increases during the reaction, most of the time for 99% conversion is taken by heating up of the substances. A smaller droplet and/or a higher hydrogen peroxide concentration decreases the decomposition time. The model gives an idea of the reaction development and decomposition times, many practical factors are not taken into account, for instance the heat capacity of the catalyst material that is heating up.

Figure 6.1: Decomposition model results for a 1% efficiency engine droplet of 35%_w HP. The vertical line indicates the time point of 99% conversion.

Figure 6.2: Energy decomposed as a function of time, for droplets of various sizes and concentrations. The point of 99% conversion is indicated.
6.4 Experiments

Experiments are performed to obtain a catalyst material with good durability and sufficient decomposition times.

6.4.1 Method

The following method was used to test catalytic surfaces:

1. Fabrication
2. Decomposition testing
3. Selection
4. Fabrication
5. Durability testing
6. Selection

6.4.2 Fabrication

Fabrication steps Generally the following steps were executed to fabricate the supported catalytic surfaces.

- Cutting: Aluminium chips were cut, circular or square, of approximately 4 cm$^2$, to serve as a catalyst substrate.
- Cleaning: The substrates were cleaned with Acetone.
- Pre-treating: Possible hydrogen peroxide treatment and/or roughened with sandpaper and cleaned again.
- Burning: The samples were treated in the oven at 400/500 °C for approximately 4 hours. Ramp ed up and down at 2 °C per minute.
- Applying: The precursor was applied on the substrate (possibly with a spin coater).
- Evaporating: The substrate was heated on a stove until the liquid was fully evaporated and no more gasses appeared from the substrate.
- Baking: The substrate was baked in the oven at 400/500 °C for approximately 4 hours. Ramp ed up and down at 2 °C per minute.

Variants Some steps of the fabrication were varied to find an fabrication optimum to reach the following goals:

1. A short as possible decomposition time for hydrogen peroxide droplets in between 0.3 µl and 1.6 µl.
2. A good cohesion and adhesion of the catalyst to the substrate. This is for a number of reasons:
   - to maintain liquid absorption capacity
   - to maintain reactivity on the entire surface
   - to avoid that detached particles move to places where:
     - unwanted hydrogen peroxide decomposition occurs
     - structures are obstructed
     - passages are blocked.
3. Find if the fabrication can be simplified compared to the method used by A. Meskers.

The variants are:
Substrate Plates of aluminium and anodized aluminium were used as a substrate. The materials are heat resistant up to at least 500 °C, have a porous surface (anodized aluminium especially), and are relatively strong and lightweight.

Pre-treatment Various pre-treatments were used to improve the adhesion and homogeneous growth of the catalyst. Treatments tried were: Roughening with sandpaper, welling the aluminium material in hydrogen peroxide and a heating step with variation in the duration and temperature.

Precursor The precursors Manganese Nitrate and Manganese Acetate (MnAc₂ and Mn(NO₃)₂) supplied in the form of a salt by Sigma Aldrich. They are dissolved in DI water.

Precursors amount Quantities of precursor solution were varied. It was tried to apply the catalyst material at once, or in several depositions, with evaporation steps in between. Spin-coating was tried as well to spread the precursor.

Baking the catalyst Baking was performed in the oven or on the stove, at various temperatures.

6.4.3 Test and selection
Details on the testing can be viewed in Appendix D.3. 35 % wet, hydrogen peroxide solution was used from Sigma Aldrich. An Eppendorff pipette (0.1-2.5 µl) was used to dispense droplets of 0.5 µl or 0.3 µl.

Decomposition testing The following experiments were carried out to examine the reaction time of each sample:

- A sequence of 0.5 µl droplets was dispensed on the catalyst with the Eppendorff pipette.
- A sequence of approximately 30 µl droplets was dispensed on the catalyst with a large volume pipette

The experiments were recorded on a high speed camera, the films were analysed (frame by frame) to deduct the decomposition times. The start of the reaction is defined as the moment that the droplet is absorbed in the catalyst. The end of the reaction is when the bubbling has completely disappeared and no new steam is arising from the catalyst surface.

Selection The catalyst samples that resulted in the shortest average reaction time were selected.

Fabrication Catalyst samples were created with small variations around the fabrication method of the selected samples.

Durability testing In order to test the long-term activity and adhesion of the catalyst, the set of tests displayed in Table 6.2 are executed on the selected chips.

6.4.4 Results
6.4.4.1 Fabrication
Details on the results fabrication variants precursor, precursor amount, catalyst baking and pre-treatments are displayed in Appendix D.5.1.

When the precursor is applied and is heating up, the catalyst develops in three steps during the temperature increase: 1. evaporation, 2. forming, 3. baking. The Manganese Nitrate precursor resulted...
in a black porous catalyst structure, the Manganese Acetate formed more like an surface coating. The MnAc precursor was unintended applied at a concentration of about 4 times lower than the MnNi₂ precursor. Due to the lower concentration and the non-porous structure, the ex-MnAc catalyst gave much lower decomposition times compared to the ex-MnAc catalyst. The optimum MnNi concentration was found to be around 0.4 mg/mm², giving a rough porous layer of about 2 mm. Cleaning and pre-baking of the catalyst substrates is very important. Because large deviations in catalyst structure and performance were observed for very similar fabrication steps, probably due to dirt and grease. The pre-treatments did not have a clear influence on the final performance of the catalyst, but they can help with the homogeneous spreading of the precursor, which is important for the cohesion and uniformity of the catalyst layer. Baking was done using the stove at full power for about an hour or by using the programmable oven with a temperature controlled ramp up to 500 K and down in about 11 hours. A clear relation between quality and baking method could not be determined.

6.4.4.2 Tests

Decomposition sequence For the porous catalytic surfaces the following decomposition steps are taking place:

1. Fuel absorption
2. Decomposition start, O₂ development
3. Reaction rate increases as the temperature increases
4. Boiling + steam ejection
5. Sudden decrease in gas ejection

This is the general sequence, the steps can clearly be distinguished for a big droplet on a reactive, porous catalyst. Steps 2 and 3 cannot be recognized for small droplet sizes (0.5 µl and 0.3 µl) because the droplets are entirely absorbed by the catalyst. Large droplets (~30 µl) are not entirely absorbed, but the oxygen bubbles are visible, appearing in the liquid lying on the catalyst. The fast increase in the flow of oxygen bubbles confirms the increasing reaction rate. Boiling temperature is reached when the liquid starts to bubble. Small droplets require much less time to reach boil temperature. Often nothing is visible during heating up, a sudden start of steam ejection confirms that the fuel has reached boiling temperature and is decomposing quickly.

On the most-active areas of the catalysts, the droplets are not entirely absorbed, resulting in a 'droplet on a hot plate effect' (figures in Appendix D). The droplet moves as a water droplet on a hot plate, decomposition takes place meanwhile. Very fierce reaction also caused blowing away of catalyst particles and small fuel droplets.

Decomposition testing Some of the first reaction decomposition results are displayed in Figure 6.3, production methods used for these samples are displayed in Table 6.3a. Not all of the samples: A to D, 1 to 6 are displayed in the graph, because the reaction time was so slow, that the end (and start) of the reaction was difficult to determine. The drawn conclusions are displayed for the different variants. Table 6.3a displays the fabrication of catalyst material as it was performed, still not all the influencing parameters are included. For example the temperature of the stove changes around a certain set-point, so during evaporation the temperature course is not the same for all samples. Later it was found that this has an influence on the way the structure of the catalyst was formed.

Durability testing The well performing chips from samples A to D are durability tested along with two sets of new chips. The qualitative results are displayed in table 6.3b, showing the amount of catalyst material that detached during the drop tests, and after the last decomposition test (e). In Figure 6.4 the average reaction time is displayed for the samples that showed good catalyst attachment and consistent decomposition times, for these samples the standard deviation is also displayed in figure 6.5. The reaction time results for all the durability tests (a to e) are displayed in Appendix D.3 for all the tested samples.
Figure 6.3: Decomposition times of 0.5μL HP droplets over various catalysts (logarithmic scale).

(a) Catalyst fabrication properties of samples A, B, C and D. Spin coating (S.C.) is performed at 2000 rpm for 15 seconds (i) or at 5000 rpm for 1 min (ii).

(b) Summary of drop test results, estimated percentage of catalyst material that detached, rounded upwards to steps of 10%.

Table 6.3: Catalyst fabrication and catalyst robustness.
Figure 6.4: Average decomposition times for the best performing chips. Droplets of 0.5 µL and ~30 µL, of 35% HP.

Figure 6.5: Standard deviations of decomposition times for the best performing chips. Droplets of 0.5 µL and ~30 µL, for 35% HP.
Table 6.4: Fastest decomposition times in ms for samples A,B,C,D.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Decomposition time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>26</td>
</tr>
<tr>
<td>B5</td>
<td>62</td>
</tr>
<tr>
<td>B6</td>
<td>90</td>
</tr>
<tr>
<td>C1</td>
<td>30</td>
</tr>
<tr>
<td>C2</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 6.5: HP decomposition time for 0.5µL droplets, test programs (a) and (d), the two best performing samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Reaction time (a) [ms]</th>
<th>Reaction time (d) [ms]</th>
<th>St. dev. (a) [ms]</th>
<th>St. dev. (d) [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B6</td>
<td>42</td>
<td>45</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>F5</td>
<td>39</td>
<td>39</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Best performing substrates  Samples B6 and F5 are selected as being the best performing catalysts for a aluminium and an aluminium anodized substrate, a summary of their decomposition times is given in table 6.5. Sample B6 had some decomposition testing before the durability testing was executed, its original performance would probably be slightly better. This result means that the current catalyst shows a reliable full decomposition within 50 to 60 ms, which translates to a decomposition frequency of 10 Hz if the decomposition has to complete within half a cycle. The amount of catalyst detachment from these samples was very little.

6.4.4.3 Coupling to decomposition model

The way the decomposition takes place: the heating up, the exponential increase of reaction rate and the sudden formation of steam, confirms the results of the modelled reaction.

The model was able to predict reaction times as a function of droplet size and HP concentration. Data was acquired to assay the reaction time dependency on droplet size, but there was no time to assess this.

6.4.5 Conclusion

The best catalyst sample showed an average reaction time of 39 ms for droplets of 0.5 µl hydrogen peroxide (35% wt). This sample was made using a Manganese Nitrate precursor, the results taken are after two drop tests and after the decomposition of more than 200 µl of HP solution. The decomposition time and reliability combined with a robust catalyst adhesion/cohesion gives a promising result for application of the catalyst for the actuator application.

6.5 Discussion

For a two stroke 27 Hz actuator, the reaction and expansion has to take place within 18.5 msec, which is not met yet. Ways to further decrease the reaction time are:

- A further increase of the surface area to volume ratio of the catalyst compared to the fuel. This can be done by:
  - further decreasing the batched fuel size:
    * by increasing the number of decomposition areas,
    * as a result of a higher conversion efficiency: the droplet size will be smaller than 0.5 µl when the efficiency is above 3 %.
  - Increasing the speed and change the way in which the fuel approaches the catalyst surface.
  - Increasing the BET surface area of the catalyst.
- Increasing the hydrogen peroxide concentration, according to model predictions this alone could bring the reaction time under 18.5 ms.
- Results of earlier tests showed that the manganese acetate precursor gave higher activity than the nitrate precursor. Successful implementation, possibly combined with the porous structure from the nitrate precursor, could improve the current activity.
• Applied to the integrated actuator, the temperature rises inside the reaction chamber during operation, which enhances the reaction speed.

• Shorter reaction time is needed when the fuel deposition is started before the expansion cycle starts. Because part of the reaction time is used by absorption and heating up, which does not involve much gas development. Also during the last part of the decomposition, the exhaust stage could start. This decreases the efficiency. The earlier the decomposition is finished at the expansion stage, the higher the attainable thermal efficiency.

• Stabilizers present in the HP might decrease the reaction time, when distillation is used to increase the HP concentration, the absence of these stabilizers can increase the reaction rate.

Important considerations when decreasing the reaction time:

The low HP concentration that was used, will cause a limited area of catalyst to saturate with water after a number of decompositions. From a concentration of about 70 %\textsubscript{wt} all the water that is present will evaporate. This concentration is approximately needed to achieve reliable reaction times at long term operation. Reliable reaction further depends on steady state temperature and water drainage, the last is important for a great part of the evaporated water is likely to condensate during the expansion.

Increasing the reaction rate is likely to have a limit because at a certain moment the reaction takes place faster than the absorption. At this point the total decomposition time is not decreased any more, it can even be increased due to the ‘droplet on a hot plate’ effect. Further, when the reaction rate is higher but the absorption is still faster, the loads on the catalyst material are increased. The effect of this was shown by blown away catalyst particles and droplets during the fastest decompositions.

**Fabrication**

The fabrication method used was successful, key components are: a clean substrate, homogeneous spreading of the precursor, evaporation step in 5 to 10 minutes and baking at high temperature (400-500K).

**Measurement**

The optical measurement method that was used, provided sufficiently accurate decomposition times and allowed the examination of the reactions in detail. Though a balance had to be found between frame rate and image quality. The measurement method is time consuming though for the analyses of numerous decompositions. Heat and pressure measurements might be desired as well, but a solution for the microliter droplet dispensing has to be found.

### 6.6 Conclusion

Repeated production of highly active manganese oxide catalyst on (anodized) aluminium was successfully carried out. The best catalyst sample showed an average reaction time of 39 ms for droplets of 0.5 µl 35 %\textsubscript{wt} hydrogen peroxide with a standard deviation of 10 ms. The reaction time is in the order of the desired MAV frequency. The achieved production of catalyst material is acceptable for further examining the proposed actuator concept, an actuator frequency below 10 Hz should be used for the reciprocal design. It was confirmed that going to smaller scale increases the reaction rate of the catalytic reaction. This is probably a result of the larger ratio of catalytic surface area to fuel volume. The catalyst production processes are not entirely understood, an optimum was found in production variants by empirical research and succeeded to simplify the earlier process.
Chapter 7

Integration

The working principle of the actuator design is tested by integrating the critical components that were selected and researched. The core of the design is formed by the fuel delivery system and the execution of reaction. This system is formed by integration test design I. The device is expanded in integration test design II with a closed reaction chamber in which expansion can take place. The components that are not researched thoroughly but are necessary for the completion of this device will be occupied by temporary-solution-components. This involves the storage, the expansion method and exhaust method.

7.1 Test design I

7.1.1 Design

This device is based on capillary concept I, in which fuel flows from a capillary tube via a pin-hole structure to obtain fuel exchange and reaction. The design is displayed in Figure 7.1a, it consists of two parts: An upper rod that functions as the fuel storage, transport and accumulation below the tube. The lower rod carries the catalyst material and the pin, to start the fuel exchange. Alignment of the two parts is aided by a cone shaped edge at the lower piston and an inverted shaped hole in the upper piston.

Compared to the capillary concept, the fuel delivery system is mounted upside down. This is chosen because it becomes easier to drain the liquid reaction products. In this situation it is only water. Also the integration of the part with a storage facility is easier because the flow to the entrance of the capillary tube is easy in this lay-out. The shape of the liquid meniscus at the end of the tube is better because it bends more outward due to gravity. Less penetration of the pin into the hole is required. It is chosen for one fuel delivery tube, so that the concept remains as simple as possible.

7.1.2 Fabrication

Test design The first test design with approximate dimensions is displayed in Appendix E. The dimensions of the CFDS are chosen such that a fuel volume is delivered that corresponds to the energy need in the final actuator (1% efficiency). The upper and lower rods of the test design are made from a 6 mm aluminium rod, using turning and drilling. The capillary tube is made of steel with an inner diameter of 0.7 mm. It is glued into a hole of the upper cylinder. The pin on the lower rod is about 0.3 mm in diameter and 0.6 mm in height. These dimension are chosen such that the pin is able to penetrate the tube without touching it, by making use of the cone fitting (in case the rods are vertically aligned).

Catalyst Catalyst material is fabricated on the lower rod, around the pin. The method is a repetition of the extensive production method that was selected in Chapter 6, Subsection 4.5. The production of catalyst layer had to be repeated several times. A sand-blower was used to clean the rod from old catalyst material.

Suspension The device is suspended by poly carbonate leaf springs of about 12 cm length and 2 cm wide, made of plate material with a thickness of 1.5 mm (Figure 7.1b). The upper cylinder is fixed by using cross connection. At the intersections, the struts are glued together. The lower cylinder is allowed
to move up and down by a parallel leaf-spring construction. This set-up is chosen because the lower cylinder can oscillate in a near vertical fashion with more stiffness in the other motion direction.

7.1.3 Method

Before the following tests are carried out, the two rods are carefully aligned.

**Capillary fuel delivery system** Firstly, only the working of the fuel exchange is tested between the capillary tube and the lower rod with pin. The catalytic material is not applied yet and the storage is filled with fuel. The test is done by pushing the lower rod upwards and shortly letting the two rods come together. If fuel is transferred during this operation, the lower rod is dried and the procedure is repeated.

**Reaction execution** Secondly, the occurrence of reaction is tested in combination with the CFDS. The activity of the catalyst material on the rod is tested first by using a pipette to dispense fuel droplets. Then the lower rod is placed in the set-up and it is observed if a reaction takes place when the two cylinders are shortly brought in contact.

**Resonance** Finally, a resonating test is done by giving the lower cylinder a small impulse, such that it starts to resonate while the lower cylinder touches the upper at least once. The goal is that the small reactions taking place during each cycle, give pulses to the system such that the resonance is maintained.

7.1.4 Results

**Capillary fuel delivery system** The fuel extraction is not completely constant for each touch (but the contact time also varies). After a short touching of the two rods, a droplet had accumulated at the edge between the pin and the horizontal surface of the lower rod. The size of the droplet increased when the duration of touching was longer. An estimation of the droplet size is 10 µl, for a touch of less than half a second. The fuel extraction is not completely constant for each touch. The capillary force in the tube could provide a liquid column of about 1 cm, which allows the storage to function as it was designed.

**Reaction execution** The first attempt to fabricate the catalytic material failed, even though the same procedure was used as before. The first attempt showed inferior attachment of the catalyst to the
aluminium rod. The porous structure developed less compared to the catalyst structure that was formed on the substrates.

Separate tests with dispensed hydrogen peroxide drops on the catalytic material showed that the first reaction was very fast, but during the following reactions the reaction time increased rapidly.

Reaction is taking place when the upper and lower rod touch each other. The reaction is not executed as fast as with preceding experiments on aluminium substrates. The catalytic surface deteriorated clearly after each reaction. Pieces of catalytic material were found suspended in the water from the reaction.

The difference in catalyst performance could be caused by:

- The ratio between catalytic material and dispensed fuel is probably lower, therefore the catalytic layer is much sooner saturated with water.
- Another type of aluminium support: The cylinders were made of EN AW 6082 aluminium and the plate of was made of EN AW-1050A aluminium. Both are rolled, but the compositions are slightly different.
- Surface quality differences: The rods are turned at the surface where the catalyst is attaching.
- Oil: While turning the rods, cutting oil was used. The oil probably disturbed the catalyst production, even though the pieces were acetone cleaned and heated before catalyst deposition.
- Temperature profile: The temperature profile on the catalyst precursor differs from that of the aluminium plates when it is evaporated, as it takes much longer for the rods to heat up (due to larger mass and smaller contacting surface area).
- Concentration: Homogeneous spreading of the precursor is more difficult on the tiny surface with a pin.

**Resonance** The frequency of the resonance is high, the vibration is clearly damped, after a pulse the vibration is stopped after 10 to 20 cycles.

The quality of the catalyst material on the first concept was not sufficient to give reaction at the frequency of the resonating suspension. Because of the high resonance frequency and repeating fuel throughput, the reaction was going on continuously. The catalyst quality improved during the several reproduction steps, but as the production and removing of catalyst was repeated, the surface of the rod wore off.

**Conclusion** The working of the capillary fuel delivery is proven, even though the volume of the exchanged fuel is difficult to control. Also, the reaction takes place after fuel exchange, but the catalyst quality was not sufficient to repeatedly obtain fast reactions.

### 7.1.5 Improvements

Some changes are proposed to improve the first test concept and the test set-up:

- The alignment of the rods by means of the conical shapes is not ideal. It allows for rotations for it aligns the rods around a point. Touching and aligning causes friction as well.
- The use of a polymer in the parallel leaf-spring system results in an overall compliant system, due to the small elasticity modulus. The possible, but undesired, rotations are a problem for the delicate pin and catalyst material.
- With the damping of the applied suspension it is not likely that the resonance is maintained by means of the open reactions in between the rods.
- The catalyst production on the rod has to be improved, especially the durability of it.

### 7.2 Test design II

A new device is designed and fabricated. Based on the first design it is tried to include the proposed improvements.
7.2.1 Design

Figure 7.2 shows the new design. A cylinder is included in the design, the two rods become pistons that partially slide into the cylinder. Multiple functions are accomplished with the new design:

- Alignment of the two rods/pistons by the guiding of the cylinder.
- Expansion of the reaction gases can take place in a closed, variable volume.
- An exhaust system is integrated via holes in the cylinder.

Expansion This design includes the expansion of the pressurized reaction gases. The normal stroke of the piston-cylinder-piston design is 6 mm, the maximum stroke is above 6.5 mm. It corresponds to the FWMAV amplitude requirement.

Exhaust The exhaust of gasses is provided by holes in the cylinder, which are closed when the lower cylinder is in its upper position. The order of motions is depicted in Figure 7.2, it is a result of a higher friction between the surfaces of the lower piston and the cylinder compared to that of the upper piston and cylinder. At the minimum volume position, the exhaust is closed. When the pistons move away from each other, the upper piston moves first, compared to the cylinder. During the last bit of the stroke, the lower piston moves relative to the cylinder such that the exhaust opens. When the system reverses to minimum volume, this order is reversed. This creates a closed volume while the volume increases (expansion) and an open exhaust when the volume is reduced. The difference in friction should be induced by using a smaller fitting for the lower piston sliding surface. Secondary options could be oiling the surface or adding a seal (reduces leakage and increases friction).

Temporary components In earlier chapters of this report, solutions like a piston cylinder were discarded as good solution at the micro scale. The solution that is used for this test design is meant to be temporary, for it is an easy, practical solution to obtain expansion and exhaust, to be able to prove the concept.
7.2.2 Fabrication

Test design II  The approximate dimensions of the design are displayed in Appendix E. The test device is again fabricated from a 6 mm aluminium rod, by using turning and drilling. The sleeves in the upper rod was made using milling. The inner and outer surfaces of the sliding cylindrical contact are polished with polishing paper and oil to obtain a smooth surface.

Because the margin of the "rod-rod" alignment has improved, the tube that is inserted in the upper rod is decreased to an inner diameter of 0.7 mm. Also, the pin size is increased in diameter and length, such that its size can be reduced later to fine tune the fuel exchange.

Catalyst production  The catalyst production method remained the same. The cleaning steps - with acetone and by heating - were performed more thoroughly. The calcination was only performed on the stove, directly after the evaporation step.

Suspension  Figure 7.3 shows test design II in the set-up. The set-up is made using MakerBeam, which is a mechanical construction package that combines aluminium profiled beams with T-slot technology. The beams have a typical dimension of 1 cm by 1 cm. The upper piston is fixed to the construction, a compression spring is used to suspend the lower piston to the set-up. A very compliant spring is used, to obtain a resonance frequency of less than 10 Hz.

7.2.3 Method

First, the resonance of the lower piston is tested, without fuel in the storage. The resonance is started by stretching or compressing the spring. The sliding of the pistons and the exhaust functionality are examined. Secondly, the full system is tested by adding fuel to the storage. The functions reaction, expansion and exhaust should be executed at the resonance frequency of the system. Some of the tests are recorded with a high speed camera.

7.2.4 Results

Resonance  Resonance of the device is taking place, analyses of the recorded video revealed that the resonance frequency was above 30 Hz. Due to friction of the piston-cylinder surfaces and damping in the spring, the resonance stops after a few strokes. Sometimes imperfections, misalignment or debris caused the resonance to stop very rapidly. This occurred even though the surfaces were polished and cleaned several times. Repeated polishing widened the gap between cylinder and piston.

The intended sliding sequence of the pistons and cylinder did not occur convincingly. It was tried to increase the friction of the lower piston by wetting it with oil or water. This did not help sufficiently, besides the liquids crept upwards towards the catalytic surface and made it wet. This ruined the catalyst activity in case of the oil.
Reaction  Reaction was occurring, but no short reactions with pressure pulses were observed, after a few touches, the decomposition took place continuously. The high resonating frequency prevents the reactions to finish before new fuel is deposited, also the quality of the catalyst material is not sufficient for this frequency with this amount of fuel. The attempts to start the system with an initial amplitude failed, the resonance died out after a few strokes. Surprisingly, on the video it was observed that after the system came to a standstill, the system itself came in resonance again. Which does point to a cyclic pressure build-up and pressure release even though the reaction was continuous.

It is expected that the capillary fuel delivery is more reliable due to the improved alignment, but the influence of the porous catalyst material on the absorption is unknown. Currently the working cannot be verified, because it cannot be observed.

Some leakage was observed when reaction had taken place: at the position of the sleeves, the exhaust holes, the ends of the cylinder and through the capillary tube. The later is caused by dissolved gas or by catalyst material inside the tube. When the system was excited, the exhaust was not always closed, such that pressure was build-up during the volume decrease, this caused liquid droplets to emerge from above the reservoir. Finally, the friction problems were observed during this test as well. When catalytic material was used the first time, catalyst particles loosened and therewith enhancing the problem.

Conclusions  Many of the previous problems have been solved: self alignment, higher Q-factor of the spring construction, expansion possible and a better performing catalyst material. But new problems have raised: too high frequency, exhaust timing, friction (due to tumbling) and leakage.

The intended working of the full system has not taken place. But the system was excited at its resonance frequency by a 'continuous' reaction and pressure build up with a periodic pressure release. Leakage and the non-functioning exhaust timing are not the main problems, because a properly timed reciprocal reaction would still (netto) excite the system by the expansion strokes. The efficiency is not of primary concern. The main problem is the too high resonance frequency and the abrupt increase in friction of the system.

7.2.5 Improvements

- Lower the eigenfrequency of the system to about 5 Hz. Such that the fuel is decomposed completely each cycle.
- Prevent tumbling of the lower piston.
- Decrease the leakage in the system, especially when the position is at minimum volume, the leakage through the reservoir has to addressed.
- If possible, improve the exhaust on/off switching reliability.
- If possible, decrease the friction.

7.3 Test design III

The third test design is improved by replacing the suspension of the second test design.

7.3.1 Design

The results of the changes in the second test design is displayed in figure 7.4. The upper piston is clamped by a push-bar into a corner (Fig. 7.4 Right). The lower piston is suspended by four double leaf springs. It is chosen for this construction because:

- A vertical perfect linear motion is obtained.
- The stiffness of the structure can approximated easily and precise. Hence the eigenfrequency of the suspension including components can be designed very specific.
- The structure is relatively stiff in the displacement directions other than the intended direction.
- Use of spring steel in this construction allows a very low damping.
- It is relatively easy to change the eigenfrequency if needed.
7.3.2 Fabrication

**Suspension** The exact material of the spring steel could not be identified. The plates were cut from a strip with a width of 13 mm and a thickness of 0.1 mm. Eight identical leaf-springs were made with a length of 110 mm. The dimensions were calculated using the known masses, densities and the desired eigenfrequency of 6 Hz. The stiffness of the structure was derived using the 'verget mij nietjes'. The leaf-springs were spot welded together, connections to the set-up and plastic holder were made with glue. The holder was made of poly carbonate, a hole of about 6 mm was drilled for the lower piston.

**Catalyst** The old catalyst material was removed using sand-blasting, the fabrication method was repeated. Small and big droplets of fuel were applied until the catalyst material was saturated. This was done to check the robustness and to remove weakly attached particles.

7.3.3 Method

The method of the second test was used again. Before the lower piston was reinstalled, the catalyst activity was checked again.

7.3.4 Results

**Resonance** Some effort had to be put in the correct alignment of the complete structure. Once this was achieved, all benefits of the system became apparent. The eigenfrequency was about 5 Hz, the Q factor very high, including the sliding test device, the system resonated for more than 10 cycles. The motion of the lower piston was linear and vertical, which allowed the cylinder to move smoothly over the pistons. Due to gravity and the low friction, the cylinder rested on the lower piston when in motion, hence the exhaust remained closed. The exhaust holes opened after the cylinder reached the ultimate position of the pin and sleeve.

**Reaction** The reactivity of the catalyst was good, short reaction times were achieved with small fuel droplets.

Reactions occurred in the complete device. Occasionally a short reaction was seen, with steam escaping from the exhaust and from space between other surfaces. Oscillation tests were not successfully, the problems of leakage and continuous reaction were not solved. It was observed that large volumes of fuel were exchanged from the capillary to the pin, perhaps the contact time was too long for the dimensions of the system.

Also it was observed that a droplet was dispensed from the CFDS system after the lower piston was moved away. Apparently the pin is not always able to extract the droplet from the tube. A similar effect was observed in earlier experiments: if the meniscus under a tube filled with liquid, is touched, a droplet starts to grow under the tube. For a certain critical volume, the droplet grows continuous, even when the contact was already stopped.
**Conclusion**  There was no time to implement a solution to prevent back-flow through the storage and it remained a problem. Closing the storage using a lid will probably allow the CFDS to give one or multiple fuel deliveries. More advanced solutions would be a one-way valve or a channel with a large back-flow resistance.

The CFDS does not provide reliable amounts of fuel, which is a big problem. Tuning of the system was not tried, it is likely to be very time-consuming, with no guaranty of success.

7.4 Improvements/ideas

**Glass**  The use of glass or other more hydrophilic materials than aluminium could help to extract the droplets. Together with decreasing the capillary size and penetration depth, it is a more likely way to obtain reliable droplet extraction of small size.

**Other Materials**  The choice of materials is limited due to HP compatibility and reactivity, working temperature, water absorption (polymers), weight and strength. PMMA is the current best known material, it is compatible with HP, but has working temperature up to 80 °C, which becomes a problem when the reaction decomposition chamber temperature rises to 100 °C due to repeated reactions.

7.5 Conclusion

Problems that have overcome:

- Production of the catalyst on the actuator component is different from the production on small plates. Activity and cohesion problems were overcome, but still needs to be improved.

- Fabrication: The smallest available mill was used. One of the smallest drills and tubes that were available were used. The fabrication could fully be performed on conventional milling and turning machines, but clearly it reaches the limit. Reducing the size by an order of magnitude is probably possible when micro or precision milling and turning machines are used, computer controlled preferably. But the parts will become very fragile and difficult to handle and assemble. The glueing of the inner tube inside the upper piston was already a little challenge.

Problems that have to be overcome

- There is a fundamental problem in the dosage inaccuracy of a capillary system, there are a lot of factors such as: contact time, (catalyst) surface roughness and temperature which influence the fuel amount that is exchanged. If the repeated working of the capillary fuel delivery concept is verified, this inaccuracy problem can be solved with active control.

- The leakage through the storage during reaction is still a problem for the integrated capillary fuel delivery system.

- Improvements can be made by the selection of other materials. This is essential for the CFDS, but also an option to temporarily improve friction and sealing.

The two-stroke catalytic decomposition concept has not yet been proven. More effort has to be put in the realization and testing of this or improved devices.
Chapter 8

Conclusions and Discussion

General

The liquid energy converter concept that is developed shows that, to obtain mechanical power by a stand alone system, the use of chemical energy is feasible at this scale. In terms of power to weight ratio it is likely to outperform electric actuators. Depending on the efficiency that is achieved in the converter, the stored to mechanical energy density of hydrogen peroxide can be higher than that of batteries.

Most of the current projects that develop chemical energy converters at micro or meso scale, do not include all components that are necessary to achieve a stand alone system for the conversion of fuel to mechanical or electrical power. In this project, the integration of functions is considered from the start, a device with all critical functions combined was tested already at a very early stage of the development.

A wrap-up of the entire design process is given in this chapter, a conclusion with discussion is given for each design step:

Functional design choice

The route to an functional design, described in Chapter 3, has drastically confined the design space. This allowed to develop and test an actuator concept to a far extend in the available time. The analyses of actuator functions allowed to characterize and compare the core functions in meso-scale. Together with the compatibility considerations of these functions, this determined the complexity and expected performance of the design.

The chosen functional design allows for integration and synchronisation of the FWMAV with the expansion and reaction function. Generation based on pressure expansion allows for a process with the right balance between efficiency and power/weight ratio. The possibility for the choice of a 'batched' reaction function was based on HP decomposition experiments from earlier work. Desired benefits of the reciprocal reaction and expansion are: use of reaction pressure peaks and decrease of heat loss due to short term temperature increase. Micro scale problems as friction, wear and leakage can be avoided in this concept.

Current developments of the chosen functional design give hopeful perspectives in the sense of energy throughput, producibility and mass. But it is not certain yet, whether this actuator concept is able to meet the requirements for the MAV. As the developments on micro scale show, a lot of progress can be made in spite of the scale complications. This is shown for instance by the advancements made in the development of combustion and rotating devices. Rotating generators are attractive because of the possibility for high frequency operation and hence a high power/weight ratio. A reciprocal system is preferred due to simple coupling to the resonating body and because the increased problems of rotating devices at small scale can be avoided. This makes it more likely to end up with a higher efficiency conversion.

Working concept

The two-stroke internal catalytic decomposition actuator shows that the functional design choice can result in a very simple actuator design. The concept generates work specifically for the Atalanta resonating body flapping MAV, which allowed integration of functionalities in components and a very simple actuation control. The design is carried out without the use of sliding surfaces. The simplicity by integration and the decrease of micro scale problems makes the design attractive at the meso-scale and an promising platform for further scaling down.

Considerations for the working concept:
• The power is delivered by relatively short pulses in the actuator cycle. It is not verified if this is an appropriate work input for the FWMAV. It is important that the work transfer is efficient and that intended efficient wing flapping motion is not disturbed by the input, by induced resonances or induced accelerations. If the input is problematic for the FWMAV, solutions could be smoothing of the actuator output by storing elastic energy or making a lay-out with a double expansion in each cycle.

• The current actuation location of the actuator is probably not the best. Most of the forces on the resonating FWMAV go through the locations where the wings are attached. The majority of the effective mass of the resonating system is located at the wings and the aerodynamics loads act especially on the wings, while the potential energy of the structure is saved especially in the thorax structure. If the actuation location needs to be changed, but the actuator orientation is not, a solution could be the application of extra linkages.

Capillary fuel delivery system In theory, application of a capillary fuel delivery system is very attractive: there is no driving power required, there are no added losses or friction, the system consists mainly of open channels and no valves or moving parts are required. In mechanical static situation, the flow in the system is a function of shapes and materials, which can be determined by design. Fuel exchange in a repeated contact could provide an exact amount of fuel during each contact. The result is that the system can be very simple, lightweight and robust. A phenomenon increasingly present at micro scale is used instead of being a source of annoyance.

In practice, a sufficient fuel flow rate was achieved and the capillary action is able to dominate gravity and accelerations on the system. But to the writers opinion, a lot of effort has to be made to make this concept a reliable and efficient solution. Concerning the forces on the fuel, the capillary should dominate. This implies small channels, i.e. a high surface to volume ratio. On the other hand: to achieve fuel exchange, the fuel has to be approachable at the surface, such that it can come into contact with the decomposition unit. A temporal flow potential is required to the moving unit, which has to provide a reliable exchange of fuel amount. In practice, the exchanged fuel volume is a complex function of time, position, shapes, temperature and pressure. Currently, this process is not controllable and only to a certain extend determined by the design and production. This results in dynamic deviations in the supplied fuel per stroke, which leads to insufficient or inefficient power strokes.

There are two ways to make the capillary action driven fuel delivery system feasible for the final actuator. By making a design that transfers fixed fuel amounts during each contact, such a system might consist of very tiny and complex shapes combined with specific materials or surface treatments. Another way is an addition of control, such that the system deviations that occur can be compensated. If these options take away the initial benefits of the CFDS, other fuel driving methods should be considered.

Reaction The major goal of this work was to assess the feasibility of the catalytic decomposition for the reciprocal concept. The results were promising, but the ultimate required reaction times have not yet been achieved and the catalyst material fabricated was very delicate. The achieved products are sufficient to test catalytic actuator concepts, but the production method comes very precise, and the condition of the support material influences the product and performance a lot. Much work has to be done to get a mature catalyst material, that can be used in a functioning device. The major goals are:

• Decrease the reaction time to below half the FWMAV frequency.

• Achieve reliable reaction time during numerous repeated reactions.

• Keep the integrity of the catalyst material while this is achieved.

This can be achieved using:

• Increasing HP concentration to at around 70%_{wet} or higher. This allows for:
  
  – faster decomposition times.

  – A dry catalyst material after decomposition, which allows for more reliable reaction times and less heat loss due to present liquid water.

  – Higher energy density, hence longer flight time.
Deposition of smaller droplets which allows for shorter reaction times.

The increase of reaction rate is limited when a porous structure is used. At a certain point the reaction speed is higher than the absorption rate. The benefit of a high specific surface area is then strongly decreased. The proposed measures also increase the load on the catalyst. Therefore, it is suggested to focus on the robustness of the catalyst while the reaction speed is increased using the two methods. The robustness could be increased by:

- Using a thinner catalyst layer.
- Using surface treatments on the substrates to enhance the adhesion (proposed in Chapter 6).
- Apply a stronger porous layer on the substrate before catalyst application.
- Using a non-porous catalyst for example: solid material, sliced honeycomb catalyst, or sputtered material.

**Integrated test concepts** The test devices that were fabricated showed that the primary functions can be combined in a very simple system. Fuel delivery and reaction were achieved in the device, slight working of a cyclic expansion was observed. The weight of the device that included the expansion and exhaust, was around 5 grams. It is possible to decrease the weight to below 1 gram by removing non-functioning material, giving promising perspectives for the mass requirement of the actuator. The system has not shown full work strokes performed by expansion. The main reasons are leakage, friction and continuous reaction due to fuel overload.

Improvements for the integrated design are:

- Improving accuracy and reliability of the CFDS system. New CFDS plus decomposition unit ideas can be tried, like a sponge with a non-porous catalyst (Appendix C.6).
- Including of a system that avoids back flow to the storage tank during reaction or compression. Smart solutions can be provided by open channels with a large flow resistance in one direction like the Tesla valve, which has no moving parts.
- Reaction time and reliability needs to be improved, design changes for the integrated design:
  - Including a larger catalytic surface area, such that the fuel absorption capacity of the decomposition unit is increased.
  - Use of more fuel exchange areas, but this increases the requirements for the alignment.

Most functions of the actuator are not yet examined in detail, critical functions that need to be examined:

**Expansion and exhaust** Micro scale problems are not avoided with the use of the temporary expansion and exhaust components, they are not suited for the final actuator. Radically different expansion methods should be tried, some ideas are balloons, welded bellows and sealed springs or cylinders. The dimensioning of the expansion system determines the thermodynamic expansion cycle. Stiffness and compliance are important factors that determine the motion resistance, the dissipation due to deformation and the achieved maximum and minimum volumes. Parallel development of the expansion and the exhaust is recommended, the timing and deformations of the expansion can aid the exhaust functionality. A well performing expansion and exhaust system is one of the important criteria to obtain an efficient and powerful system.

**Storage** The storage function has not given much attention, in combination with the current CFDSs the component is more demanding. Some ideas are explained in Appendix C.6.

**Suspension to FWMAV** A lot of requirements were listed for the coupling to the FWMAV (Section 3.2.2). The function can be developed at a late stage, but the stiffness characteristics are very important for the transmission efficiency and flapping performance.
**General**  It is important to constantly monitor the cooperation and integration during the development of components. For example, the current CFDS concepts requires alignment of the decomposition unit, this might be a more challenging aspect for other expansion methods. More ideas on components are found in the morphological overviews of Wageningen [51] and Meskers[41].

**Materials**  Some research was done to find appropriate materials, there are many requirements for the materials applied in this device. Some high performance plastics are able to meet the requirements and can be used to decrease the weight (Appendix F).

**Future projects**  One of the desires is to scale down the actuator. Challenges will be faced in the production and assembly of the actuator also by the effect of scaling on heat conduction. Heat management will be a key point to maintain efficiency, a solution could be recirculation of heat to the fuel storage.

   Control, communication and sensing of the MAV will require electrical energy. An interesting source could be an electric generator, integrated in the decomposition actuator.

   When the decomposition actuator concept has been realized successfully, the chemical conversion can be taken a step further by the use of HPGP or similar mono propellants (Chapter 1). The means of catalytic decomposition can be maintained while the energy density of the fuel is drastically increased. However, some advantages of the current process will disappear.

**Is this the right way to go?**  The integrated approach has brought a very interesting basis for a stand alone MAV micro actuator. The actual performance that can be achieved by the actuator is discovered only when the development makes progress, by means of decisions in the design. New knowledge and experience will prove if the design choices made were adequate, one has to go back in the process regularly to reconsider the chosen path.
Chapter 9

Recommendations

Critical components  It is important to proceed the development with the critical components. Work has to be done on the components reaction and fuel delivery. It is advised to develop the systems separately, possibly in parallel, before integrating again.

- Develop the fuel delivery system to ensure that constant, defined fuel amounts are delivered each stroke. Consider including a simple means of control. It might turn out that the application of a total different system is needed, which is more complex, but advantageous due to reliability and experience.

- For the development of reaction, focus has to be on the increase of robustness, meanwhile the catalyst should be prepared for higher concentrations of HP.

The critical component expansion and exhaust are of equal importance at this stage. It is advised to develop these functions together.

- Focus should be on a design that has little or no leakage, has low or non dissipative resistance and is light. A thermodynamic model, including losses would be useful to determine the optimal dimensions.

Integration  While the progress is made, the integration steps needs to be kept in mind. The following functions need to be addressed in the reintegration.

- A system to avoid back pressure through the fuel delivery system.

Of secondary importance are the functions:

- Shapes of the storage component are limited when the internal volume is increased, even special adjustments might be needed for the integration with the CFDS system.

- Suspension of the device to the FWMAV. Important is a definite set of requirements for work input of the resonating body FWMAV.
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Appendix A

Functional design

Details on generator motion type.

Rotary motion type There are important practical implications when it is decided for a rotary type of generator. At macro scale, rotary generators - Rankine cycle turbine, turbo-fan engines etc. - stand for durable, efficient systems. At smaller scale however, this is not (yet) the case (Section 1.2). The efficiency and life-time of rotating generators decreases considerably when scaling down and a high power to mass ratio has been achieved though.

Rotary components have a few benefits. They offer a steady state generation process, which includes steady and predictable pressure and temperature profiles. Besides, they can run on very high frequencies so they can potentially have very high power to mass ratios. On the other hand, rotary components often include bearings and vanes or discs, which are more difficult to fabricate than non-rotary systems. Loads and losses are continuous and non-cycling for this type, there will be spatial areas of elevated temperature and increased pressure.

Linear motion type + Reciprocal input Many of the properties of a rotary generator are inverted for the reciprocal, linear generator. This type of generator does not necessarily have sliding surfaces, for example a bellow can provide expansion of a gas. Problems of friction, wear, lubrication and leakage can - in principle - be avoided with a smart design. A reciprocal engine has the drawback of accelerating and decelerating masses, which can cost energy, induce resonances and disable smooth running, which altogether limits the frequency. Pressures and temperatures change in time and location. In terms of losses this can either be a benefit or a draw-back and in terms of structural load it is a draw-back (fatigue).

Linear motion type + Continuous input The continuous and linear input is only practical for the momentum engine. A linear and continuous heat or pressure process means that there is a single ongoing stroke to perform all work during the cycle. In order to perform sufficient work, the stroke must be very long, or it has to involve very large forces. This is not practical, nor it is likely to result in a system with a high power to mass ratio. This solution is an generator, operating at nearly 0 Hz: one cycle during over several minutes. The momentum, continuous and linear type of generator has a very proven elaboration at various scales and also with the use of hydrogen peroxide. It is the nozzle, a very simple, robust and lightweight generator, offering a very high power to mass ratio.
Appendix B

Working concept considerations

The expected challenges of the critical functions are listed here. The list is used to find the important and challenging aspect of the concept. Factors per critical function:

1. Refuelling
   - capillary action
   - possible pressure build-up/variation
   - safety issues concerning high concentration hydrogen peroxide
   - material compatibility

2. Fuel transport
   - changing pressures in storage chamber
   - changing pressures in reactor
   - temperature variation (cyclic)
   - fluid flow friction
   - capillary action
   - gravity
   - accelerations
   - diffusion

3. Fuel accumulation
   - acceleration
   - gravity
   - hydrophilic/hydrophobic
   - condensed water
   - pressure variation
   - temperature variation (time)
4. Reaction execution
- temperature variation
- pressure variation
- fuel concentration variation
- fuel quantity variation
- fuel accumulation variation
- exhaust species
- wear of catalyst material

5. Reaction timing
- absorption (capillary action)
- reaction time
- amplitude variation of the FWM
- Contact area
- forces

6. Expansion
- decaying pressure
- decaying temperature
- condensation
- timing/coupling by resonating body
- hydrogen peroxide compatibility
- many repeated deformations

7. Exhaust
- gases and liquid water
- decaying pressure
- decaying temperature
- timing/coupling with resonating body

8. Suspension
- Different kinds of resonances/motions/accelerations
- Amplitude variation
- Start-up procedure
Appendix C

Surface tension

C.1 Capillary flow model

The force balance:

\[ F_c - F_g - F_v - F_i = 0, \]  
\[ \text{(C.1)} \]

with \( n \) the number of tubes, \( d \) the tube diameter and \( h \) the height of fluid in tube. The capillary force is given by:

\[ F_c = n\pi d\gamma \cos(\theta), \]  
\[ \text{(C.2)} \]

with \( \gamma \) the surface tension and \( \theta \) the capillary angle. The gravity force is given by:

\[ F_g = \frac{n\pi}{4} d^2 \rho gh. \]  
\[ \text{(C.3)} \]

The viscous force is given by:

\[ F_v = n8\pi \mu \frac{dh}{dt}, \]  
\[ \text{(C.4)} \]

with \( \mu \) the dynamic viscosity. Finally the inertia force is given by:

\[ F_i = \rho A_t \left( h + \frac{V_0 - h A_t}{A_s - A_t} \right) \frac{d^2 h}{dt^2}, \]  
\[ \text{(C.5)} \]

\( V_0 \) is the total liquid volume, \( A_s \) is the surface area of the storage, \( A_t \) the surface area of the tubes. \( A_s \) is the surface area of the storage, \( A_t \) the surface area of the tubes.

given by:

\[ A_s = \frac{\pi}{4} d_s^2 \]

and

\[ A_t = \frac{n\pi}{4} d_t^2. \]

Assumptions:

- For as well the capillary as for the viscous force, only contributions of the forces inside the tubes are accounted for. Because it is assumed that the effect of the surface area is much larger inside the tubes than elsewhere.

- The gravity force due to the fluid inside the tubes, results from the height of the fluid column above the fluid level in the storage. The extra gravity force due to decrease in storage fluid height is neglected.

- The viscous force is derived with the Darcy-Weisbach equation [56].
\[ \Delta p = f_D \frac{L \rho u^2}{2}, \]

with \( L \) the length of the pipe and \( u \) the average flow velocity. The flow is assumed to be laminar, so the friction factor \( f_D \) is equal to \( 64/Re_D \).

- The derivation of the inertia force was found by assuming that the storage is cylindrical shaped with surface area \( A_s \). The height in the storage cylinder changes during the fluid flow, when the liquid flows from the storage to the tubes, the acceleration can be calculated. The total amount of liquid is \( V_0 \), it is assumed to be the constant storage volume.

**Order reduction** The differential equation now has the form:

\[
C_c - C_g h - C_v h \frac{dh}{dt} - (C_i + C_u h) \frac{d^2 h}{dt^2}
\]

Solving this equation would end up in a very complex function, it is tried to simplify the function to obtain an ordinary differential equation (second order).

Further assumptions to simplify the model:

- The viscous force is a function of the height and the velocity of the fluid in the tube. Assuming that the traveled length of the fluid is (much) smaller than the initial height in the tube, one can choose a constant value for the fluid height in the tube. For example the ultimate height.
- The inertia force can be simplified by using this same assumption such that \( h \) becomes \( h_0 \) and is only dependent on the 2nd order derivative of \( h \).
- Realizing that the storage volume is about 5*60*30 as large as the liquid displacement volume (when the tank is at least half full). And that \( A_s \) is about 10 to 100 times larger then \( A_t \). This means that ....

The differential equation that follows is:

\[
C_c - C_g h - C_v h_0 \frac{dh}{dt} - C_i h_0 \frac{d^2 h}{dt^2}
\]

The solution is:

\[ h(t) = C_c/C_g + c_1 e^{(\lambda_+ t)} + c_2 e^{(\lambda_- t)} \]

With the two exponential factors derived by:

\[ \lambda_+ / \lambda_- = C_v / C_g \]

The determinant can be real or imaginary, indicating that the fluid level can be oscillating. The constants can be found by applying the initial conditions: \( h(0) = h_0 \) or \( L = h_0 \). The height of the fluid in the tubes can be calculated by using the equilibrium height (determined by where the channel opens) and the amount of liquid taken by the catalyst (reaction amount). \( \frac{dh}{dt}(0) = 0 \) The velocity of the liquid at start is zero.

The constants are then:

\[ C_1 = \frac{(h_0 - C_c/C_g)}{(1 - \lambda_+/\lambda_-)} \]

and

\[ C_2 = -C_1 \lambda_+ / \lambda_- \]

**C.2 Contact angle measurement**

Example of a contact angle measurement A photograph of one of the measurements is displayed in figure C.1. The left droplet is just deposited before the picture was made. The right drop is from one of the previous measurements, it became smaller due to evaporation.
Verification  A manufacturer of polymer capillary tubes [42] gave approximate contact angles for water with some polymers. For Polycarbonate an angle between 70° and 80° was given, which is somewhat lower than the 88° from the measurement. For PMMA an angle between 62° and 73° was given. 63° was found in the measurement which falls in the range. The surface tension of hydrogen peroxide is higher than that of water, see graph at figure C.2. Using Young's equation this means that the contact angle of a liquid solid interface with HP should be smaller than that of water. This confirms the general trend of the DI water and HP measurements.

C.3 Capillary experiments

Experiments were done to investigate some effects of capillary action. 2-D channels, reservoirs and openings were designed in SolidWorks, which were laser cut in 4 mm thickness PMMA. Each device consisted of three layers that were glued together. The internal channels were tested with water.

Results

- Rapid capillary rise of water in square channels of 1 by 4 mm was observed (figure C.4a). It took around 40 ms for 2 to 3 mm of fluid rise, which is 8 to 12 µl. Lifting the water filled sample out of the water showed that about 4 mm of water height is maintained due to capillary action (b). Changes in fluid level were very abrupt, much hysteresis was observed when water flowed to or from the channels.

- Comb structures showed a similar effect (figure C.4c,d,e). A comb with spaces of 2 mm and 4 mm thickness is not able to keep water in between the combs due to gravity (c), a comb of with spaces of 1 mm is able to hold water in between the slabs (d). Even when a strong acceleration is applied some of the water sticks (e), the applied acceleration was approximately 5 g.

- A sample with channels that ended with a smooth opening did not give ‘droplet’ forming on top of the rounded edges. When the sample was held upside down, a droplet is formed under the channel subsequently, the droplet grows, then the water continues flowing down via the walls.

- A channel of 1 mm was made with 0.75 mm PET foil sandwiched in between of PMMA plates. Water flowing inside the channels clearly showed a meniscus and an upward flow in the order of centimetres.
Figure C.3: SolidWorks drawing of a capillary experiment device, this particular design is shown in figure C.4. Photograph of capillary experiment devices.

Figure C.4: Capillary experiments with laser cut PMMA samples. Flow velocity, static equilibrium and acceleration were tested.
### C.4 Model evaluations

The feasibility of the concepts is checked using the model. The CFDS has to deliver a certain amount of fuel within the duration of one FWM cycle. The amount of fuel accounted for is the fuel volume (35 %<sub>wt</sub> HP) that carries the amount of energy, needed for a 1 % efficient engine.

**Concept 1** Theoretically, the allowed channel length and cross sectional area are determined by the properties of the solid and liquid used. Graph 5.3b shows the static fluid height in a tube, approximated by the model. The fluid amount that is needed results in a liquid level change of about 0.5 mm, this is the approximate distance the pin has to penetrate into the channel. As for sizes, dimensions and response time this concept seems feasible, but Graph 5.3b also shows that not all materials will result in a feasible design. For as when capillary action opposes gravity, a 1 mm aluminium tube only pulls up the fluid about 0.5 mm. That is not sufficient taking into account the structure and fuel level variations in the storage, smaller tube diameters would make the pin-hole fitting difficult. Variables as the shape, cross sectional area, the materials and the number of channels, can be changed to obtain the desired performance.

**Concept 2** Due to the angle of the conical hole, the vertical force component of the capillary force is decreased. When the angle is 30 °, the force is related to the cosines of (θ + 30 °). Also, as the liquid rises, the mass of the liquid in the cone increases disproportional. A small model is made to examine the equilibrium position of the liquid in a cone preceded by a straight tube section. The equilibrium of forces is given by:

\[
Ah = B + Ch^3,
\]

with \(h\) the height of the liquid from the bottom of the cone. Contribution of the capillary force \(A\) is dependent on \(h\), \(B\) gives the gravity force of the straight tube, the mass of the liquid in the cone contributes as a function of the height cubed times \(C\). The length and diameter of the tube and the angle of the cone are varied to examine the equilibrium height of the cone. For two tube sizes and different cone angles, some model results are displayed in Table C.1. The wetting angle used is 40 °. According to the model, the liquid accumulated in one cone is more than the fuel volume needed in one work stroke of the actuator. The calculation concludes nothing about the stabilization or rise time. In practice, the contact angle is probably larger.

Factors for calculating the static equilibrium height of liquid in a cone:

**Capillary contribution:**

\[
A = 2\pi\tan\varphi\cos(\theta + \varphi)\gamma,
\]

with \(\varphi\) the cone angle and \(\theta\) the contact angle. Contribution of the tube that precedes the cone:

\[
B = \rho g \left( L_1 d_0^2 \frac{\pi}{4} - \frac{\pi d_0^3}{8 \times 3 \times \tan \varphi} \right),
\]

it is corrected for the lowest part of the cone that ‘penetrates’ the tube. \(d_0\) and \(L_1\) are the diameter and length of the tube. The mass of the liquid in the cone (as a function of \(h^3\):

\[
C = \rho g \times \tan^2 \varphi \frac{\pi}{3}.
\]
Figure C.5: sequence of snapshots showing spontaneous capillary rise and auto-ejection of droplets under microgravity. The inner diameter of the glass tube is 9.2 mm in the straight section, and the liquid is PDMS of viscosity 0.65 cP. The drop volume is roughly 20 ml. The photos are taken 0.1 s apart. Experiment of Wollman & Weislogel [40].

**Concept 3** The principles behind this concept are not entirely understood, therefore a theoretical estimation of the liquid displacement is difficult to make. The principle is examined with experiments.

**Concept 4** Previous calculations and experiments showed that the transport rate of liquid in straight channels was sufficient. In this concept the choice of tube diameters is free, but limited by the required flow rate. There has not been found a way to model the fluid flow of this hydrophilic surface concept. A combination with concept 3 (surface droplet) might be desired to allow the liquid to flow on the surface.

**Concept 5** For the horizontal channels it is easy to approximate the static equilibrium position of the liquid, the height of the liquid in the channels will be approximated. A rectangular shaped channel is assumed with a length much larger than the width. The equilibrium height $h$ of the liquid is then found with:

$$h = 2 \eta \cos(\theta)/(g \rho w).$$

With surface tension $\eta$, contact angle $\theta$ and channel width $w$. The properties of 35% wt HP with PMMA are used. The formula gives that the height scales linearly with the groove width, for $w$ is 2 mm, the height that is found is 3.3 mm. The bad case scenario required liquid volume is easily achieved in this concept. The time required to recover the equilibrium after absorption is difficult to calculate, but the system is likely to be sufficiently fast, for the equilibrium height calculated lies much above the required depth. Multiple thin channels can be used to provide the fuel to the grooves, the exact shape of the grooves can be played with. Alignment of the decomposition unit, the translation and rotation, are important in this concept.

**Concept 6** The spontaneous capillary-driven droplet ejection is demonstrated in a film [33], a sequence of snapshots is given in Figure C.5. Under the earth’s gravity condition an experiment was carried out with tubes in acrylic [40, 60]. The tubes had a length of 5 mm an inner diameter of 1.5 mm, auto-ejected droplets had a volume of about 0.2 µl. The actuator’s bad case scenario required a fuel amount of 1.6 µl per stroke, this would require eight tubes for the shown droplet ejection example. The time required for the rise plus ejection of the liquid is about 15 ms. That is about the duration of one stroke of the actuator cycle. The experiment was probably carried out with water. In order to repeat ejection, the liquid has to be pushed in the tube. A small calculation showed that the power required for 8 tubes of 1.5 mm is less than 1 mW (to overcome the capillary force).

**General** The accumulation position and configuration of the fuel can change due to accelerations, rotations and the fluid level in the storage facility. It is expected that these difficulties can be overcome.
Accelerations and rotations can be dominated by the capillary force if the system is designed well. If during operation, the storage liquid level changes strongly, its effect can be decreased by applying a sponge-like material on the inside for instance. A sort of 'zero gravity tank' is obtained that decreases/takes-away the effect of pressure from to stored liquid mass.

C.5 Details capillary concept measurement results

Concept 1  The flow step height was similar for the various tube diameters, this is because the height between irregularities is similar. The volume rates differ a lot because the tube diameter changes while the rise times are of the same order. The rise time estimations is not very accurate, because the displayed fluid flows were within one movie frame for the 0.6 and 0.9 mm diameter tubes.

Lasered holes: The flow in the 1.5 mm diameter tube showed slow, but steady upward flow, it took about 10 seconds to reach the top of the 4 mm length tube. Clearly the speed decreased when the height increased. The first and last bit of fluid flow in the 0.5 mm lasered tube was a bit slow and unsteady, but in between it reached very high fluid motion 2.6 mm in 50 ms. The repeatability of the capillary action in the laser holes is better than that of the drilled holes.

Concept 4  A droplet deposited on the untreated PMMA surface resulted in an angle of approximately 80° compared to 20° after the treatment, clearly the surface became more hydrophilic. The effect was similar for the hydrogen gas and the oxygen gas, as well as when the sample was treated subsequently with plasmas of both gases. The flow test showed that the channels were filled with water due to capillary action, but the upper surface was not wetted due to the extra attraction. The meniscus in the channel showed a smaller contact angle. The hydrophilic property decreased over time.

Conclusion capillary concepts  The upward fluid flow rate achieved in straight channels was proven to be sufficient for providing fuel flow for the actuator concept. Flow rates of 94 and 64 µl/s were achieved in tube diameters of 0.5 and 0.9 mm, while 44 µl/s is the required flow rate. The first channel was made by laser, which provided quite steady and reliable flow. Channels fabricated using drilling, did lead to fast fuel flow jumps, but the flow was not consistent and reliable. Close-up images revealed that the surfaces in the drilled channels were very uneven and rough. The tests of concepts 2, 3 and 6 did not succeed due to the fabrication quality. Except for concept 6, their working cannot be verified or denied yet. The experiment with the hydrophilic surface concept was successful, but showed that the plasma treated surface did not pull up the fluid out of the channels. Short touching of surfaces, of which the lower one has channels, can cause liquid flow out of the channels onto the surface.

Factors that determine and limit the size of the channels are: flow rate, rise height and accessibility for the decomposition unit. The surface quality is very important to obtain fast and predictable capillary flow. Laser cutting gives a sufficient surface quality, but 3-D shapes cannot be created and the size is limited by the laser spot size. The material used gives a certain adhesion with the liquid, this can be modified/improved by surface treatments.

C.6 Ideas

Ideas for fuel storage facilities that would be compatible with the CFDS's that were designed are given in Figure C.6b. Examples A and B take away the effect of gravity due to increased surface area for capillary action in the upper storage section. Tank C is stretchable - with a certain volume, stiffness ratio - such that the pressure due to weight is approximately zero on the channel intrances. Tank D has barely any height change as the fuel is consumed.

Apart from this, hydrophobic surfaces could be used as well for confined fuel accumulation.

An idea for an alternative CFDS is given in C.6a. For this concept it is important that the catalyst is solid and robust, for the catalyst surface should not leave particles on the sponge. The decomposition amount could very well be controlled by the catalyst surface area.
(a) Capillary fuel delivery using a porous, flexible material (e.g. sponge) and a solid non-porous catalyst.

(b) Ideas for 'zero gravity tanks'; fuel storage facilities that would be compatible with the CFDS's that were designed.

Figure C.6: Ideas related to the CFDS system.
Appendix D

Reaction

D.1 Catalyses theory

Catalyses is the change in chemical reaction rate, caused by the participation of a catalytic material. As a result of the exchange of electrons between catalyst and compounds, the activation energy of the molecules is lowered. According to Do et al. [15] the heterogeneous reaction of hydrogen peroxide on a solid catalyst can be modelled with a second order reaction:

\[ r = k(T)[A][B] = k(T)[H_2O_2][catalyst] \] (D.1)

This equation gives the rate of reaction, as a function of the rate constant \( k \) and the concentrations of the fuel and catalyst in mol/l. For a single rate-limited thermally activated process, the rate constant \( k \) is given by the Arrhenius relation:

\[ k = A e^{-E_a/(RT)} \] (D.2)

\( A \) is the pre-exponential factor, \( E_a \) is the activation energy in J/mol and \( R \) the universal gas constant in J/molK. The absolute temperature \( T \) is the only variable in this equation.

D.2 Model

Model simplification In the current design there is a repeating reaction. Often reactors are continuous and are designed in such a way that a steady state is achieved, which means spatial constant temperatures, pressures and thus reaction rates. Because the reaction in the actuator is not constant the temperatures will vary, probably from room temperature (the fuel), to the boiling point of water (at end of reaction). This change in temperature during each cycle has a large influence on the reaction rate. Change in pressure usually has an influence on the reaction rate, for it influences the concentration of compressible substances. Because the diluted hydrogen peroxide is an incompressible fluid, pressure changes have not been taken into account.

Derivations Due to the assumption that the catalyst concentration is constant during the reaction, equation D.1 is simplified, resulting in:

\[ r = B \cdot k(T) \cdot [H_2O_2] = dC/dt \] (D.3)

With the constant \( B \) that replaces the catalyst concentration. Solving the differential equation we obtain:

\[ C(t) = C_0 e^{-B \cdot k(T) \cdot t} \] (D.4)

This equation gives the fuel concentration as a function of time and the rate constant. \( C_0 \) is the initial concentration of hydrogen peroxide in mol/l, \( k \) is the rate constant in s\(^{-1}\). The Arrhenius relation and the concentration equation that was derived are used subsequently to derive the concentration and new rate constant for each step. Values from literature are used to find the reaction parameters.
### Property | amount | unit | Property | amount | unit
--- | --- | --- | --- | --- | ---
Fuel amount | 22 | µL | $E_a$ | $6.15 \times 10^4$ | J/mol
Fuel concentration | 30 | % by m/m | A | $1.33 \times 10^{11}$ | /s
Temperature initial | 293 | K | $k_0$ | 1.46 | /s
Time step | 1 | ms

Table D.1: Left: initial condition of the modelled reaction. Right: derived reaction parameters.

**Activation energy** Hitt et al. [23] stated that the reaction rate of hydrogen peroxide increases with approximately 2.3 times per 10 degrees temperature increase. This observation is used to determine the parameter $E_a$. By rewriting the equation D.2 we can find $E_a$ which gives the temperature dependence of the reaction rate:

$$E_a = -R \times \ln(2.3) / \left( \frac{1}{T_1} - \frac{1}{T_2} \right)$$  \hspace{1cm} (D.5)

**Pre-exponential factor** Experimental results from A. Meskers are used to determine the pre-exponential factor. An average reaction time of 150 ms was found for a reaction with 30% hydrogen peroxide, 22 µl droplets on manganese oxide catalyst. The reaction was started at room temperature and performed in a closed environment. The pressure increases during the reaction but its effect on the reaction rate is neglected. The pre-exponential factor was found by running the model and changing the factor until the correct reaction time was found. The reaction time that was given is assumed to be the time of 99% fuel conversion.

The initial condition is given by the left side of table D.1 and the results for the reaction parameters is given on the right.

### D.3 Reaction test method details

**Droplet dispensing** The hydrogen peroxide solution used is 35 % \textsubscript{w/w}. HP was used from Sigma Aldrich. Fuel volumes needed for a 1 % and a 5 % efficient conversion are 1.6 µl and 0.32 µl respectively. It is tried to batch-test, a fuel amount of that order. Testing smaller amounts of fuel is useful, for the fuel amount can be deviated over multiple droplets in the actuator. The smallest dispensing amount that was possible, was provided by an Eppendorf (Reference) pipette, with the dispensing capability of volumes in between 0.1 µl and 2.5 µl. Droplet volumes of this size do not separate from the tip naturally, when dispensed. A finger pulse on the tip was used to free the droplet. Using this method it succeeded to reliably dispense sequences of 0.3 µl droplets. With some more effort, droplets of 0.3 µl could be dispensed. Observation of the droplet dimension confirmed that the intended volume was dispensed. Normally the pipette gives a systematic error of 8 % and a random error of 5 %, when dispensing 0.5 µl droplets. Larger deviations are expected using this unconventional method. The droplets were dispensed from approximately 10 cm height on the sample.

**Decomposition testing** Figure D.1 shows the test setup that was used for hydrogen peroxide decomposition testing. The following experiments were carried out to examine the reaction time of each sample:

- A sequence of 0.5 µl droplets was dispensed on the catalyst with the Eppendorf pipette.
- A sequence of approximately 30 µl droplets was dispensed on the catalyst with a large volume pipette

The experiments were recorded on a high speed camera with frame rates of 300, 600 or 1200 frames per second. The recordings were analysed using one of two methods:

1. For slow reactions: the approximate start and end of the reaction were found on the film, the time difference was recalculated to obtain the reaction time.
2. For fast reactions: the exact start and end of the reaction was found by examining the recording frame per frame, the number of frames was devided by the frame rate to obtain the reaction time.
The start of the reaction is the moment that the droplet is absorbed in the catalyst, the fourth image on figure D.2. The end of the reaction is when the bubbling has completely disappeared and no new steam is arising from the catalyst surface, this is on the eleventh image on figure D.2.

The dispensing method that was used to obtain dispersion of tiny droplets, made it difficult to perform pressure measurements. It was chosen to examine only the reaction time, for it is the most important parameter. With knowledge of the decomposed fuel amount it is possible to derive the conversion power. It is important though that it is certain that (almost) all the dispensed fuel has decomposed. The experiments of A. Meskers are similar to these performed here. He found that the reaction pressure was related to the reaction time. The static pressure after the reaction revealed that the fuel was completely decomposed. It is expected that full decomposition takes place here as well, when the reactions are of a similar speed.

'Water droplet on a hot surface effect' High reactivity decompositions sometimes resulted in the 'droplet on a hot plate effect'. Figure D.2 shows a frame by frame example of such a hydrogen peroxide decomposition. The fuel droplet touches the surface from the fourth figure, steam starts to appear from Figure seven. At the eleventh figure, the decomposition has completely taken place. The reaction seems to leave no traces of water at the surface, the unevaporated water is probably absorbed by the porous catalyst.

D.4 New catalyst variants

Fabrication variants that were considered but not tried:

- Use of a porous Zirconium Oxide base layer could be tried on aluminium. Especially when the MnAc precursor is used.
- Chemical roughening was suggested to increase the adhesion between substrate and catalyst.
- Remove the catalyst material from the substrate and reattach it at the desired location.
- Manganese(Oxide) deposition with sputtering or CVD.
- Using pure Manganese or Manganese Oxide foil (this is very expensive).
- Using a method of H.H. Perez that featured sputtering of catalyst with reactivity enhancement by increasing the surface area.
Figure D.2: Decomposition recording of a 0.5 mL HP droplet, filmed at 300 frames per second. Decomposition takes place from figure 4 to 10. First and last figures lay 5 frames apart. The sample diameter is 25 mm.
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<th>calcination</th>
<th>Catalyst amount</th>
<th>calcination</th>
<th>Comment</th>
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Table D.2: Selection of fabricated and tested chips arranged per variants
D.5 Reaction test results

D.5.1 Fabrication variants

Precursor When the precursor is applied and is heating up, the catalyst develops in three steps during the temperature increase: 1. evaporation, 2. forming, 3. baking. The first heating on the stovetop causes the water to evaporate, the salt starts to attach. Secondly, when the water has almost entirely evaporated, the substance starts to bubble. The temperature increases and a solid layer or porous structure of Manganese Oxide appears. In case of the Manganese Nitrate precursor, brownish gas appeared from the surface, directing to nitrogen dioxide. For the Manganese Acetate precursor, a slimy, fleece like structure appeared before it solidified. The result looks more like a coating than a porous material itself. The final heating step is the catalyst baking. It was found that samples made with Manganese Acetate as precursor performed very poor. It was only discovered in a later stage, that the used concentration of the Manganese Acetate precursor was about 10 times lower than that of the Nitrate precursor. Conclusions on the activity and appearance of the catalyst from the Manganese Acetate precursor are therefore not definite.

Precursor amount The amount of precursor influences the final structure of the catalyst. During the second heating step, a layer or a porous structure is formed. This depends especially on the amount of applied precursor. A layer is formed when a small amount of precursor is used: below 1 ml of MnNi$_2$ per substrate (about 5 cm$^2$), or when the spincoater was used. Larger volumes of MnNi$_2$ resulted in a rough black landscape with a high porosity. The result for the MnAc was similar. The concentration of precursor was much lower, hence only when large amounts of precursor were applied the porous-like structure would form. The solidification of the bubbling slimy-fleece structure, appeared to be less open and porous compared to the Ex-MnNi$_2$ structure. For the nitrate precursor the effect is displayed in the pictures (figure D.3), not yet a figure

Spincoating the precursor at 2000 rpm for 15 seconds resulted in a very thin layer of catalyst after evaporation, at the edges the forming of a porous structure has started (Sample E1). Sample C1 shows a catalyst that has a nice porous structure, with a good cohesion. It is observed that application of a too large amount of precursor (>3 ml per substrate) leads to bad cohesion or adhesion of the catalyst after the evaporation step. Sample B3 shows that most of its catalyst material has fallen of.

Homogeneous spreading of the precursor before evaporation is very important in order to obtain a homogeneous catalyst surface and good adhesion to the surface. Applying the desired precursor amount at once, mostly gave the best results. Applying the precursor in multiple times - also when using the two different precursors combined - often resulted in detachment of the previous layer or particles. Stresses in the structure, developed by the development of new solid material is likely to be responsible for the detachment, not yet a figure

Catalyst baking From the Samples A to D, the Samples B2, B3, B6, C1 and C2 performed best, their average reaction time for 0.5 µl droplets is given in table 6.4. From these B2 and C1 had the shortest reaction times, about 30 ms. B2 and C2 are the samples that had a final baking step in the oven at 500 K for three hours, the other samples were heated on the stove for several minutes. This example shows that the exact temperature treatment of the oven is not necessary for high activity of the catalyst.

Samples C1 and C2 supported on anodized aluminum had an identical production process, only C2 was calcinated afterwards. The performance of the catalyst samples was similar, except that half of the catalyst material of C2 detached during the first drop tests, the other half during the second. Almost no reaction was occurring when test (d) was executed. Samples C1 and F5 had a similar process, except for the calcination: they give similar results for durability and reactivity.

More testing is needed to verify the definite requirements for the catalyst baking.

Pre-treatments Hydrogen peroxide: A few times the samples were covered with hydrogen peroxide, such that the oxygen layer on the aluminium would increase. The result was an easier wetting surface, especially when the manganese acetate precursor was applied. Roughening: using sand paper to roughen
the sample’s surface did not clearly improve the adhesion of the catalyst, as was shown by the detachment of material on Sample B5 compared to B6 (Table 6.3b). In other cases the roughening did not give a clear advantage.

These performed pre-treatments did not show a clear influence on the final catalyst behaviour. For very similar fabrication techniques, large deviations in catalyst structure were observed though. This is probably caused by the quality of the substrate before the precursor is applied. Influences can be:

- Greasy surface due to non-dissolved cutting oil or fingerprints: in some cases a oily catalyst surface was visible.
- Other dirt from the underground, tools or the air, the catalyst sometimes showed strange colouring and uneven spreading and growing.

Factors that influence the wettability of the surface influence how the precursor is spread and thus how the catalyst grows.

D.5.2 Catalyst durability test results

All results of the durability tests are displayed in Table D.3.
Table D.3: Durability test results.
Appendix E

Test design drawings

The drawings of the test designs are displayed here. During fabrication some of the dimensions changed.

Figure E.1: Left: test design 1. Right: test design 2. Both with approximate dimensions.
Appendix F

Material research

Schematics that show hydrogen peroxide compatibility of a few materials. And the selection of PVDF as the best performing polymer for the actuator.

<table>
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<th>Material</th>
<th>Compatibility 10% H₂O₂</th>
<th>Compatibility 30% H₂O₂</th>
<th>Compatibility 50% H₂O₂</th>
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<td>B2 - Good</td>
<td>B2 - Good</td>
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<td>B - Severe Effect</td>
<td>A - Severe Effect</td>
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Table F.2: Material selection.
Appendix G

Scaling general

This summary is given by William Trimmer [49] on the scaling applied on micromechanical devices. The force has been found to scale in one of four different ways: $[S^1]$, $[S^2]$, $[S^3]$ and $[S^4]$. If the scale size is decreased by a factor of ten, the forces for these different laws decrease by ten, one hundred, one thousand, and ten thousand respectively. In most cases, one wants to work with force laws that behave as $[S^1]$ or $[S^2]$. The different cases that lead to these force laws, the accelerations, the transit times, and the power generated per unit volume are given in figure G.1. For the force laws that behave as $[S^1]$ or $[S^2]$, the acceleration increases as one scales down the system. The power that can be produced per unit volume also increases for these two laws. The surface tension scales advantageously, $[S^{1.5}]$, however, it is not clear how to use this force in most applications. Biological forces also scale well, $[S^2]$ but may be difficult to implement. Electrostatic and pressure related forces appear to be quite useful forces in the small domain.

\[ F = \begin{bmatrix} S^1 \\ S^2 \\ S^3 \\ S^4 \end{bmatrix}, \quad a = \begin{bmatrix} S^{-2} \\ S^{-1} \\ S^0 \\ S^1 \end{bmatrix}, \quad t = \begin{bmatrix} S^{1.5} \\ S^1 \\ S^{0.5} \\ S^0 \end{bmatrix}, \quad \frac{P_R}{V} = \begin{bmatrix} - \\ S^{-2} \\ S^{-1} \\ S^0 \end{bmatrix} \]

Figure G.1: Effect of scaling on forces, accelerations, transit time and power over volume.