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Design of an injection system under low pressure and temperature conditions in liquid fuelled micro UAV’s

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Abstract

Unmanned air vehicles (UAV’s) today are extensively used for a wide range of applications, from amateur to human to military applications. Electric propulsion is preferred for small UAV’s, while piston engines and gas turbines are used for the bigger ones. The proposed engine in this work covers the midscale for restart able, low budget vehicles (<10kg and 30-200N thrust). Simplicity, durability and manufacturability are the main target goals of the design. The liquid fuelled engine is designed to run on gasoline and ethanol as a fuel and a hydrogen peroxide – water solution as the oxidizer. The advantage of the high energy density of the liquid reactants is counteracted by the difficulty for the ignition of the reactants at low pressures and temperatures, especially at the starting up process. In this work, different nozzles and injection strategies were tested and evaluated under similar conditions that exist at start up of the engine. It has been found that even for reasonable manufacturing process and precision, good atomization can be obtained if a mixture of gas and liquid is premixed prior to injection. This can be realized by catalytic decomposition of the hydrogen peroxide without the need for an extra gas supply circuit. This exothermal reaction provides the additional advantage of injecting a hot mixture in the cold combustion chamber, allowing easier ignition.

Introduction

Unmanned air vehicles (or simply UAV’s) are found in a wide range of applications, from amateur to human to military applications. Lots of small UAV’s use electrical energy for the propulsion, making them flexible, simple, save and quiet. The main drawback of this propulsion strategy is the low energy density of batteries compared to energy stored in liquid phase (cfr. left of Fig.1). As well is the speed and flight range of the vehicle limited. This is the point where turbines make their entrance. However, micro turbines used for the somehow bigger UAV’s are complex and expensive. The small dimensions require small clearances in order to maintain reasonable efficiency, while the rotating parts should be able to expand due to the high temperature. As the scale of turbo machinery is reduced, the compressor efficiency decreases and, therefore, the total efficiency non-linearly drops with its size when it is utilized in a micro-propulsion system [1]. This results in efficiencies of about 30 to 50% lower than for big turbines.

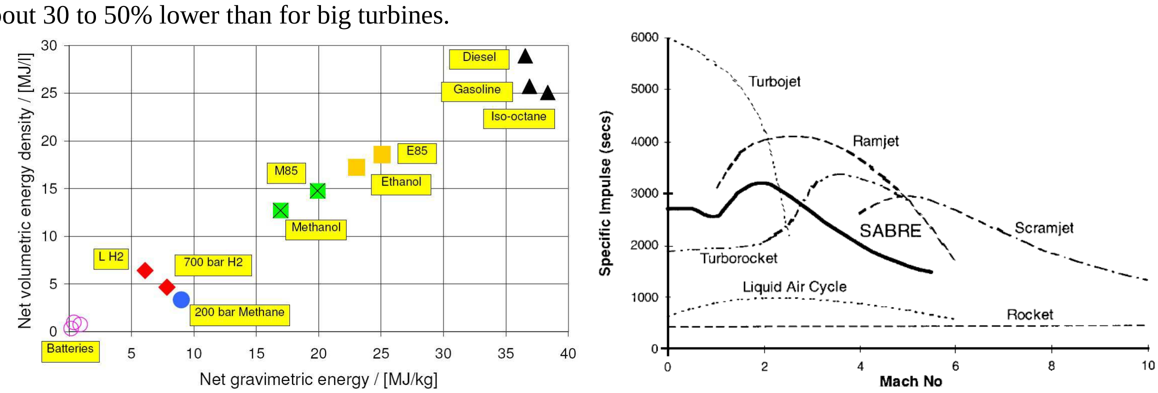

Figure 1. Left: energy densities of common fuels [2]. Right: specific impulse for different jet engines [3].

Rocket engines are the lightest of all jet engines, but the efficiency is strongly depended on the design of the nozzle, operating range such as altitude differences, chamber design temperatures and pressures. In optimized rocket engines the efficiency can be about 60% [4], for high chamber pressure and temperature, while a turbojet usually is around 30-40%.

Another measure to compare jet engines is the specific impulse I_{sp}, defined as the flow of on-board propellants required to produce a certain amount of thrust. Since rocket type engines carry both the oxidizer and fuel, the specific impulse is a lot lower than for the turbojet engine [3] (cfr. right of Fig.1). But energy is required to power the compressor as for a turbojet which can be very high [5]. For rocket engines, this energy can be stored in a gas tank to pressurizes the fuel and liquid.

The scaling of a rocket-type engine suffers the same problems as for a micro-turbine in terms of maximum operating pressure and temperature.

So apart from the drawbacks, the rocket type engine seems the suitable for the considered application the most important reasons for the choice being the lack of moving parts subjected to high temperatures and the high energy density.

The paper is arranged as follows: first, the concept of the engine is explained. The focus is drawn to the performance of the start-up and main injectors. Next, the test-rig and measurement methods are discussed, followed by an overview of different injection strategies, reactant choice and nozzle types. Some potential systems were tested and evaluated under the start-up conditions for a mixture of a gas and liquid. Based on the results, the chosen nozzle was tested with the hydrogen peroxide. Finally some conclusions and future work are tackled.

Engine concept

A cross section of the prototype test engine with most important parts and features indicated, is presented in Fig.2. The engine is designed to meet following desires

- cheap and easy to (mass) produce
- efficient and low weight
- mid-range UAV: 30-200N thrust, <15kg
- restart ability during flight
- low pressure fueling circuit (0.8-1MPa)
- save (no toxic liquids or gases)
- high durability and reliable (little moving parts)

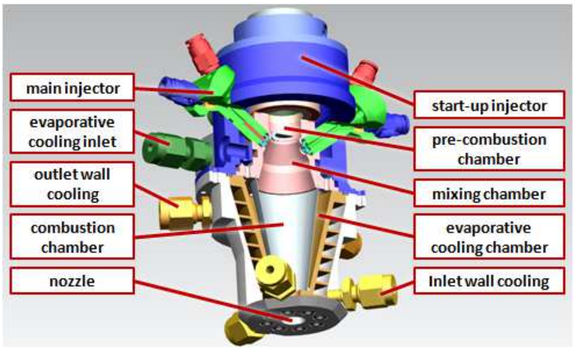

Figure 2. cross section of the prototype engine

As was mentioned in the introduction, small engines require careful design of the heat transfer, manufacturing precision and constructional complexity and weight. Furthermore, most standard available components for systems of this dimension range are limited in handling pressures and temperatures. The considered engine and surrounding components will be limited to pressures up to 1MPa due to mechanical restriction.

Pressurizing of the reactants is realized by a working gas (N_2).

The nominal chamber pressure during operation is designed to be 0.5MPa absolute. With a nominal fuel injection pressure of 0.8MPa absolute, this means that only a low pressure drop is available for the fuel injection. Proper injection for these low pressures, conditions and dimensions is not evident and is the main focus of this work.

Experimental test-rig

For study of the injection strategies and nozzle type performance, an optically accessible setup is initially required rather than a full scaled test engine (cfr. Figure 3). The experiments involve injection at ambient condition since this will be the most problematic situation for a system with restart abilities. The setup involves 3 supply lines: a liquid fuel (ethanol or gasoline), a liquid oxidizer (60wt% hydrogen peroxide (HP) - 40wt%water) and a gaseous oxidizer (pressurized air). The HP-solution and fuels are contained in a bladder in such way there is no contact with the working gas. The flow of the HP, fuel and pressurized gas are controlled with pressure based flow controllers (1). One-way valves (2) are implemented for safety and prevent the fluids to flow to the wrong tank. Solenoid valves (3) activate the injection for the desired fluid. They can be flexibly programmed for tuning and different injection strategies by varying the supply voltages and PWM signal for multiple injection. A pressure driven carburetor (4) can be installed for premixing the fuel with a gas. Finally, the oxidizer (HP) and fuel (fuel (and/or pressurized gas)) are supplied to the injector (5). The injector can be changed depending on the injection strategy used, as will discussed in section "Injection strategies" and section "Nozzle types"

Focused shadowgraph imaging is used as the high speed optical diagnostic to visualize the spray. A green high power led (7) acts as the light source and a PCO Dimax (8) captures the images at 10kHz. The solenoid valves (3) and camera (8) are simultaneous triggered, which allows the determination of the hydraulic delay.

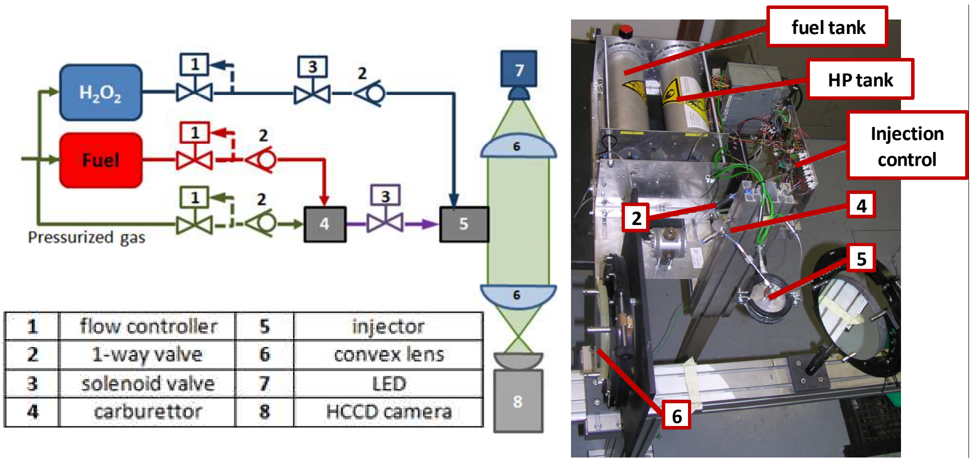

Figure 3. Schematic representation and actual implementation of the experimental setup.

Injection strategies

The limitations of this type of engine are the low injection pressures and low ambient density and temperature, which makes proper atomization difficult. For this reason, the choice the injection strategy is of extreme importance. The fuel and oxidizer can be injected in 3 different ways:

- both as a liquid
- both as a gas
- one as a gas and one as a liquid

For a proper spray combustion, the mixing process of fuel and oxidizer is the most important factor apart from the fuel and oxidizer properties. Despite the easy storage and high energy density, injection of both fuel and oxidizer in liquid phase requires time to mix and evaporate. Atomization of the injection significantly increases the evaporation and mixing rate but is difficult to achieve at such low injection pressures and ambient densities [6]. The mixing can be enhanced by mixing them beforehand and injecting this mixture through a single injector. If a gas and liquid are both injected through the same nozzle, the atomization is suddenly completely different as will be demonstrated later on. This type of injection can be most likely a liquid fuel with a gaseous oxidizer or mixture of a liquid fuel & oxidizer with an additional gas. However latter strategy might require an additional (large) tank and gas supply circuit which increases the system complexity and weight.
Finally, the solution to avoid the need for atomization and evaporation is to inject the fuel and oxidizer both as a gas. In this way, only the right mixture ratio and ignition energy is required. But, the storage of the gases is difficult and requires cryogenic, pressurized or absorption storage technology [4].

A promising compromise for the atomization problem is the use of a hydrogen peroxide (HP). Hydrogen peroxide is considered as a non-toxic, green (mono-) propellant fuel which is usually used in small thrusters in satellites or micro gas turbines [7-10]. Hydrogen peroxide has the advantage that it can be catalytically decomposed by an exothermal reaction with the formation of water vapor and oxygen:

$$H_2O_2 \xleftrightarrow{catalyst} O_2 + H_2O + heat$$

With this property, the liquid oxidizer can be transformed into a gaseous fluid prior to injection, without the use of complex and energy consuming components. Additionally, the internal energy of the injected mass is increased due to the exothermal reaction, allowing easier and earlier ignition.
The most relevant properties HP are shown in table 1 together with the considered fuels for this project. The properties of water are added as well since HP is commercially available in a water solution.
Some applications use HP as a monopropellant thruster [7], but due to the low heat release of HP compared with the gasoline or ethanol combustion, the supply tanks would become too big to keep the total energy and thrust the same. And since HP comes in a solution with water, the heat of evaporation of the water should be taken into account as well. An advantage for HP is its high density, compared with most other fuels and oxidizers [11], which is an important factor for aero application.

Nozzle types

Lots of nozzle configurations exist for many different spray and combustion applications, such as orifice, swirl, hollow cone, twin, co/counter-flow, air atomizing and spiral nozzles.

Taking the boundary condition into account, some of these nozzle technologies can be ruled out: simple nozzle holes such as used in todays piston engines use high injection pressures (~velocities) and high backpressures to create sufficient atomization and mixing. Aerodynamic forces, turbulence and cavitation. Co-flow injectors are mostly used for gaseous fuelled burners or in applications where the dimensions allow long flame lift-off lengths, such as industrial burners. Hollow cone nozzles have the disadvantage of being difficult to construct for low mass flow rates. They need very small clearance and accurate positioning in order to have a homogeneous flow pattern. Swirl and twin nozzles have shown in a lot of low injection pressure application a good atomization pattern and are both easy to manufacture compared to the others. These 2 types of nozzles are preferred the first design of this application.

	HP	**water**	**EtOH**	**gasoline**
density (@313K) [kg/m³]	1450	998	789	740
molar mass [g/mol]	34	18	46	~100
liquid heat capacity [J/kgK]	2620	4182	2720	2220
gaseous heat capacity [J/kgK]	1267	2258	1800	2000
viscosity (@293K) [mPa.s]	1.25	1.00	1.20	1.18
boiling point [K]	423	393	350	300-488
Auto ignition temperature [K]	-	-	662	465-743
heat of evaporation [kJ/kg]	1520	2443	846	180-350
Flammability limits [vol%]	-	-	3.3-19.0	1.3-7.6
heat of decomposition [kJ/kg]	2780	-	-	-
Lower heating value [kJ/kg]	-	-	27000	43000

Table 1. Properties of hydrogen peroxide (HP), water, ethanol (EtOH) and gasoline [12, 13].

The twin nozzle

Figure 4 shows a high speed imaging recording of a twin nozzle (0.35mm diameter holes, 70° angle between the nozzle channels) fuelled with only a liquid (top) and with a mixture of a liquid and gas (bottom) for different time instances after visible start of injection (AVSOI). It is noted that the terms "gas" and "liquid" are used since the liquid and gas can be both fuel and oxidizer if the injected HP is only partially decomposed. On the right sight of Fig.4 a CAD drawing and manufactured nozzle are shown. As the liquid fuelled nozzle has a good performance with the naked eye, high speed imaging reveals some defects: the fuel that was left in the injector produces a liquid sheet before breaking up (up to 5 - 6mm). During the steady state injection, the breakup length is still too long as indicated by the image scale (distance between the 2 red horizontal lines is 5mm).

In the case the fuel is premixed with a gas (bottom row of Fig.4), the atomization is almost immediately established and no liquid sheet exists the nozzle. Slightly bigger droplets are however noticed at the start of injections (cfr. 100µs and 850µs AVSOI images in Fig.4). Essentially, no further visible breakup could be noticed, but only dispersion of the droplets. The breakup mechanism is mainly caused by the friction forces between the fast moving gaseous oxidizer and fuel inside the small nozzle holes.

In order to improve the atomization at start of injection, the gas valve was activated a little earlier than the liquid fuel valve. Nevertheless, no significant difference was detected. This can be explained that as both valves are energized equally, the gas flow reacts faster than the liquid flow, resulting in a similar effect of an earlier opening gas valve.

Apart from the difference in droplet size, the faster penetration can be detected in the case of the premixed injection, as well as the smaller spray angle (about 66° for the standard twin nozzle and only 57° for the fuel-gas mixture injection); the droplets in the premixed spray are significantly smaller and have a much smaller inertia. When the 2 jets collide, the droplets are much easier deflected. In the ideal case (complete symmetry and same momentum for the 2 jets), all the fuel should flow along the injector axis. A faster penetration is mainly established by the higher injection velocity, which follows directly from the basic Bernouilli equation when the same injection pressure is used.

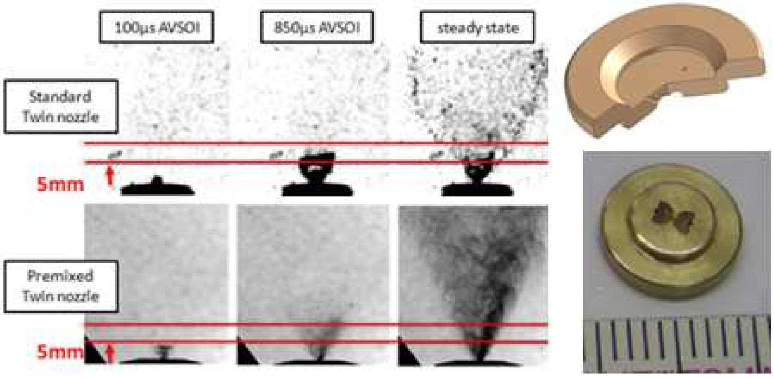

Figure 4. upper row: the standard twin nozzle spray, bottom row: premixed twin nozzle spray at 3 different timings AVSOI. (Shadowgraph @ 20kHz), right: cross sectional and realized image of the nozzle (0.35mm holes, 70° angle between nozzle holes)

The flow rate of the gas and liquid were varied in order to understand the nozzle behavior in the different operation conditions. Low flow conditions for both are not considered since this condition is not relevant for the application as the injectors will be used near maximum operating pressure. Qualitative results are shown in Fig.5. Similar conclusions as earlier can be given: the atomization improves with gas flow, while the spray angle decreases with the gas flow. From the qualitative spray cross section, it was found that the higher the gas flow, the more the spray approaches a full cone angle which gives the best dispersion for a given spray angle. As the gas flow decreased to zero, the spray pattern tends to form a planar spray and became more sensitive to the machining accuracy. The spray pattern was very similar for all different tested nozzle types operating with a mixture of liquid and high gas flow.

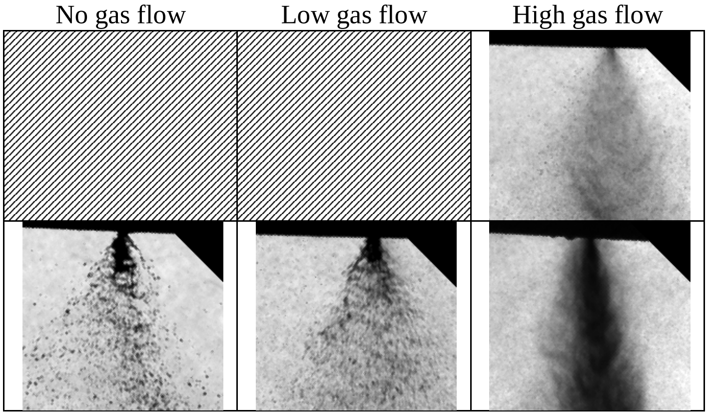

Figure 5. overview of the performance of the twin nozzle injector for different liquid and gas flow rate (distance between red horizontal lines is 5mm

The triple nozzle

With the idea to increase the atomization capabilities of the nozzle when using a small or no gas flow, a triple nozzle was manufactured, similar to the twin version. The same total mass flow (or flow area) can be obtained with smaller holes which improves the atomization. However, no additional improvements were noticed and the nozzle was prone to the injector position and manufacturing process, resulting in spray with an important angle offset. This is the main reason why this concept is not further investigated.

The swirl nozzle

A swirl nozzle was constructed and is visualized at the right of Fig.6. At the left side high speed images for the single liquid fuel (top) and premixed injection (bottom) are shown as well as a cross sectional drawing and manufactured nozzle.

The idea of swirl nozzles is to create a rotating fluid motion, turbulence and mixing by injecting the liquid and/or gas into a chamber by eccentric placed holes. Due to this rotating motion the droplets are forced to move outwards by centrifugal forces and to create a high dispersion as a result. Tests were performed with the swirl nozzle as shown in figure 6. Two swirl nozzles were tested, one with a nozzle throat diameter of 1mm and the other with 2mm.

Since the length of the swirl chamber was rather long, the spray was much less affected by the manufacturing process and a symmetric spray was noticed under all conditions.

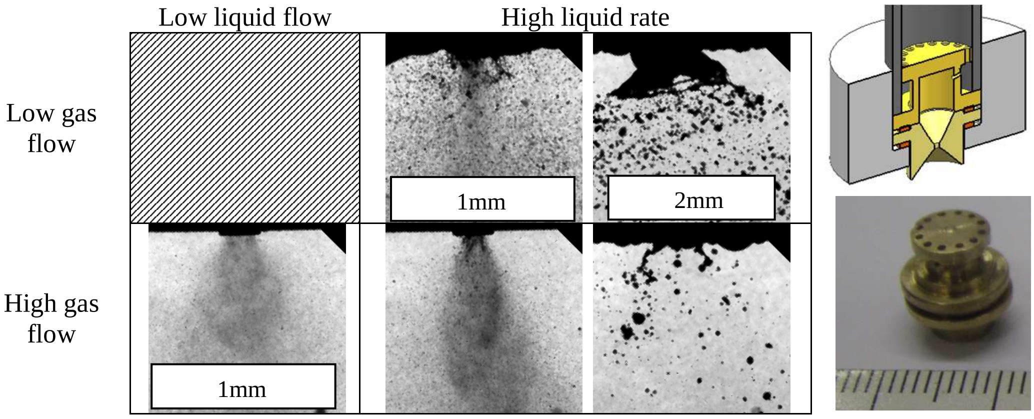

Figure 6. Left: overview of the performance of the swirl injector for different liquid and gas flow rate, with "1mm" indicating a throat diameter of 1mm; "2mm" a throat diameter of 2mm, Right: CAD cross section of the used swirl chamber

For most of the conditions, the atomization was poor and decreased with the increasing liquid/gas ratio. For high liquid and low gas flow a liquid sheet was formed as was the case for the twin nozzle without gas flow. Strong differences exist between the 1mm and 2mm throat diameter. This can be explained by the fact that the atomized liquid droplets when entering the swirl chamber, will hit the wall of the swirl chamber. Even at high liquid & gas flow rates and throat diameter of 1mm, bigger droplets were notice at the boundary of the spray, originating from the wall film.
This liquid film is driven towards the throat. The smaller the throat, the higher the gas velocity, which encourage again the breakup. As a conclusion, swirl nozzles are not in favor for the a fluid composed of liquid and gas.

Towards the injector design

Earlier discussion showed that atomization under atmospheric conditions with liquid injection is difficult, but realizable with a proper chosen injection strategy. For the application, catalytically decomposed hydrogen peroxide will be used. The considered concentration of HP in water is 60wt%. This choice has the advantage that the temperatures are low enough to mix with the fuel inside the injector with chance of auto-ignition, to ensure a high life expectancy of catalytic bed and to keep the combustion temperatures at affordable levels. Furthermore, this concentration of HP is still commercially widely available.
Due to the small dimensions of the engine (and injectors), it is not expected to have a fully decomposed HP at the exit of the nozzle, but rather a mixture of gas and liquid, as was studied in previous sections.
It has already been reported many times in literature [11] that the design of the catalytic bed is the biggest issue in the injector performance. Many different types of catalysts and catalytic beds were already investigated in the past, ranging from simple and commercially available to exotic and expensive ones [7, 14].

Several options were investigated in the framework of this application, but the optimal configuration for long term use was not yet found. The main problems that came up were the loss of catalytic material and the poor contact surface-to-volume ratio. The other difficulty is the rather high water concentration which lowers the rate of temperature increase at start-up. Examples in literature usually make use of HP concentrations higher than 80wt%, with the HP as the propellant [8, 10, 11]. In this way they suffer less from the wet and low temperature issue, they suffer from a low life-time of the catalytic bed. With a new installed catalytic bed, the MnO_2 granules (about 0.7-1mm) and a MnO_2-activated ceramic honeycomb-like structure give good performance. A perforated copper plate with holes of 0.6mm in diameter is installed before the nozzle to create a sac volume and to prevent the holes from clogging by the MnO_2 granules. Additionally, this sac volume assures an equally distributed mixture over the nozzle holes to avoid asymmetric spray. The cross section of the injector is shown in Fig.8.

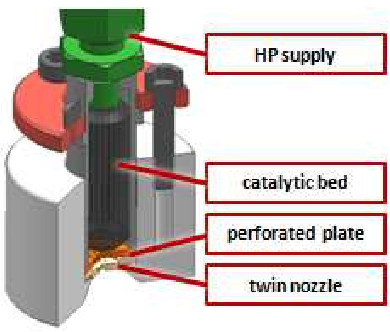

Figure 8. Design of the tested HP injector.

A small rocket-type engine with restart ability requires 2 injection strategies:

- injection at start-up conditions: atmospheric pressure and temperature
- injection at nominal conditions: high temperature, higher pressure (5bar in current application)

It is not required that both strategies should be realizable with a single injector: the start-up injection doesn't have to produce thrust, but rather to create a hot, reacting atmosphere for the main injection. Considering this application, separated designs seem to be the most efficient for 2 reasons: a limited amount of injectors can be installed in the combustion chamber head due to the small dimension and mechanical restrictions. This would imply that the mass flow rate will be high. For the starting up situation, this would imply a high loss of fuel and oxidizer. The lower the flow, the better the catalytic decomposition can occur and the faster the injectors and chamber can heat up, as the catalytic reaction increases with temperature.
As a conclusion, a single centralized injector for low flow rates will be installed for the start-up sequence. The main injectors will be positioned around the center directed towards the start-up injector.
The main differences between the injectors will be the flow rate and the size of the catalytic bed. Low flow rates but highly decomposed HP (so big catalytic bed) is required for the start-up injector.

The performance of the HP injector strongly depends on the conditions of the catalytic bed: a wet and cold catalytic will react slower. From experiments it is found that the humidity dominates. Figure 9 shows the start of the HP injector with a wet body temperature of 40°C. It takes about 500ms before a reasonable atomization is obtained. For a cold but dry catalytic bed, the steady state is almost immediately reached with noticeable droplets and the spray is very similar as for the high gas flow situation investigated in previous sections.

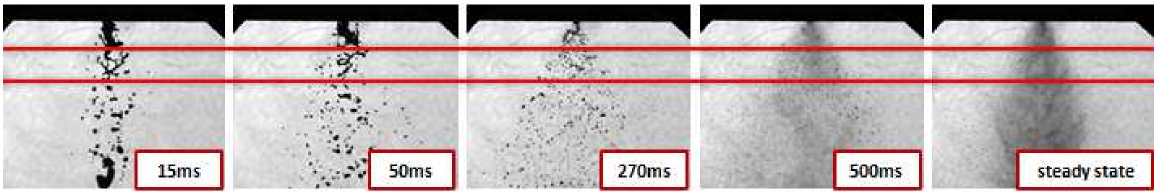

Figure 9. start-up of the HP injector (with 0.35mm twin nozzle) with a wet catalyst at 40°C at different time instants after visual start of injection. Distance between the 2 horizontal lines represents 5mm.

Future perspectives

The proof of concept is shown in this work, but additional work is required in the design of the catalytic bed. Improvement of the surface-to-volume ratio is one of the potential factors in which is lot of improvement possible. Spray combustion was not yet considered in this work, but will be intensively studies, in terms of ignition and emission formation.

Conclusions

In this work, nozzles were studied for operation in a small UAV rocket-type engine under low temperature and pressure conditions and restart ability. Twin, triple and swirl nozzles were selected and investigated by a high-speed shadowgraph diagnostic. Atomization was significantly improved by the injection of a gas-liquid mixturerather than only liquid. With this observation, catalytically decomposed hydrogen peroxide was proposed as an oxidizer for this engine concept. A prototype injector was constructed and tested in terms of atomization. Following conclusions were drawn:

- Triple nozzles give no additional advantages and are more prone to the injector position and manufacturing defects
- Swirl nozzles have a very poor atomization when the gas flow becomes low and bigger droplets are noticed in all condition at the outer boundary of the spray
- Due to the gas flow, twin nozzles produce a full cone spray rather than a planar spray, as can be expected from a pure liquid injection
- The HP injector is very sensitive to the used catalytic bed: a wet bed significantly descreases the starting capabilities of the injector
- In steady state operation, the HP injector provides spray patterns similar as for the liquid-gas mixture tests.

Acknowledgements

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