Liquid monopropellant injector development for high power electrodeless plasma thruster

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LIQUID MONOPROPELLANT INJECTOR DEVELOPMENT FOR HIGH POWER ELECTRODELESS PLASMA THRUSTER

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Abstract

The thesis work aims at developing a liquid monopropellant injector for a high power electrodeless plasma thruster. The feasibility of using a chemical monopropellant for electric propulsion is investigated. After a design phase, the injector is put to the test with a simulant to the real liquid monopropellant in a simulated environment. Theoretical models are created to predict the power needed to vaporize a mass flow of the monopropellant without decomposing the heavy molecules. Testing has proved that the injector is able to vaporize the simulant of the real monopropellant. The properties of the propellant are compared to that of Xenon and Argon, showing good and promising results.
Acknowledgments

First I would like to thank Romain Delanoé for his support through the thesis work. It proved very productive to bounce ideas off each other. Romain did not only reason with me through my thesis but also helped with reviewing the report.

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Nomenclature

$I_{sp}$  Specific impulse
$\omega_c$  Cyclotron frequency
$q$  Electric charge
$B$  Magnetic field strength
$m$  Mass
e  Electron charge
$E$  Electric field strength
$v$  Velocity
$\omega$  Electromagnetic frequency
$f$  Force
$F$  Force density
$\omega_p$  Plasma frequency
$n_0$  Plasma density
c0  Vacuum electrical permittivity
$\mu$  Magnetic moment
$V_e$  Exhaust velocity
g0  Acceleration at the Earth’s surface
$P$  Power
$T$  Thrust
$\dot{m}$  Mass flow
$E_{ion}$  Ionization energy
$\alpha_{ion}$  Ionization efficiency
$R$  Ideal gas constant
$\Delta H_{fus}$  Enthalpy change of fusion
$\Delta H_{vap}$  Enthalpy change of vaporization
$T_B$  Boiling point at standard pressure
$C_p$  Heat capacity
$\sigma$  Stefan-Boltzmann constant
$\varepsilon$  Emissivity
$\varepsilon_{eff}$  Effective emissivity
$\alpha$  Absorptivity
$k$  Thermal conductivity
$h$  Convective heat transfer coefficient
# Acronyms

<table>
<thead>
<tr>
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<th>Description</th>
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<tr>
<td>AA</td>
<td>Ammonium Acetate</td>
</tr>
<tr>
<td>ADN</td>
<td>Ammonium DiNitramide</td>
</tr>
<tr>
<td>AN</td>
<td>Ammonium Nitrate</td>
</tr>
<tr>
<td>AP</td>
<td>Ammonium Perchlorate</td>
</tr>
<tr>
<td>CP</td>
<td>Chemical Propulsion</td>
</tr>
<tr>
<td>CPS</td>
<td>Chemical Propulsion System</td>
</tr>
<tr>
<td>DN</td>
<td>DiNitramide</td>
</tr>
<tr>
<td>ECAPS</td>
<td>ECological Advanced Propulsion Systems</td>
</tr>
<tr>
<td>ECR</td>
<td>Electron Cyclotron Frequency</td>
</tr>
<tr>
<td>EIMPaT</td>
<td>Electrodeless Ionization Magnetized Ponderomotive Accelerator Thruster</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>EP</td>
<td>Electric Propulsion</td>
</tr>
<tr>
<td>EPS</td>
<td>Electric Propulsion System</td>
</tr>
<tr>
<td>FOI</td>
<td>Swedish Defence Research Agency (Totalförsvarets forskningsinstitut)</td>
</tr>
<tr>
<td>GEO</td>
<td>GEostationary Orbit</td>
</tr>
<tr>
<td>GTO</td>
<td>Geostationary Transfer Orbit</td>
</tr>
<tr>
<td>HDN</td>
<td>DiNitramide acid</td>
</tr>
<tr>
<td>HPEP</td>
<td>High Performance Electrical Propulsion</td>
</tr>
<tr>
<td>HPGP</td>
<td>High Performance Green Propulsion</td>
</tr>
<tr>
<td>HPLC</td>
<td>High-performance liquid chromatography</td>
</tr>
<tr>
<td>IP</td>
<td>Ionization Potential</td>
</tr>
<tr>
<td>KTH</td>
<td>Kungliga Tekniska Högskolan (Royal Institution of Technology)</td>
</tr>
<tr>
<td>LMP</td>
<td>Liquid Mono-Propellant</td>
</tr>
<tr>
<td>MPD</td>
<td>Magnetoplasmodynamic</td>
</tr>
<tr>
<td>OHB</td>
<td>Orbital High-technology Bremen (Orbitale Hochtechnologie Bremen)</td>
</tr>
<tr>
<td>$P_{\text{min}}$</td>
<td>Minimum Power</td>
</tr>
<tr>
<td>$P_{\text{nom}}$</td>
<td>Nominal Power</td>
</tr>
<tr>
<td>$P_{\text{max}}$</td>
<td>Maximum Power</td>
</tr>
<tr>
<td>PRISMA</td>
<td>Prototype Research Instruments and Space Mission technology Advancement</td>
</tr>
<tr>
<td>PT</td>
<td>Pressure Transducer</td>
</tr>
<tr>
<td>SSC</td>
<td>Swedish Space Corporation</td>
</tr>
<tr>
<td>TC</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>VASIMR</td>
<td>Variable Specific Impulse Magnetoplasma Rocket</td>
</tr>
<tr>
<td>VG</td>
<td>Vacuum Gauge</td>
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Chapter 1

Introduction

1.1 Project Overview

This Masters Thesis was carried out between the 2nd of April and the 30th of September 2012 at OHB Sweden in Solna. OHB Sweden, a member of the OHB AG Group, is a provider of space systems. The company develops, builds, tests and operates satellites for various kinds of space missions within communications, earth observation, space research and exploration.

The High Performance Electric Propulsion (HPEP) project started with the idea to use the excess power provided by the solar panels on a satellite during a transfer between a geostationary transfer orbit (GTO) and a geostationary orbit (GEO). An Electric Propulsion (EP) thruster could use this excess power and therefore be used for the apogee raising maneuver. However, the geostationary satellite would still need chemical thrusters for attitude control or any other high thrust maneuver. Because of this fact, the HPEP project aims at using a chemical propellant for both propulsion systems. This implies that both propulsion systems could share the same propellant tank: one Chemical Propulsion system (CPS) for the attitude control and one Electric Propulsion System (EPS) for the apogee raising maneuver.

A new promising monopropellant is the Ammonium DiNitramide (ADN) based LMP-103S developed by ECAPS, a subsidiary of the Swedish Space Corporation (SSC). This propellant is considerably less toxic and simpler to handle than the common Hydrazine. The High Performance Green Propulsion (HPGP) thruster using ADN based propellant, also developed at ECAPS could be a possible match for the HPEP project.

The HPEP project is focused on developing a EP thruster utilizing the chemically energetic LMP-103S. The electrodeless plasma thruster currently being developed by the Elwing Company is a new promising EP thruster because of the fact that it is electrodeless and it will not suffer from the electrode erosion the chemical propellant would create in an EP device using electrodes. The ionization of LMP-103S is studied and an injector to the thruster is being developed at OHB Sweden.

1.2 GEO and GTO

Geostationary orbits (GEO) are circular, equatorial orbits at an altitude of 35,786 km. A satellite in such an orbit has an orbital period equal to the rotational period of Earth, i.e a sidereal day. Thus, it hangs above the same geographical location at all times. For an observer on Earth, the satellite appears to stand still. This implies that these satellites do not need to be tracked. Most GEO satellites are communication satellites or weather satellites.

Since a GEO satellite can only be located at a certain altitude and exactly above the equator, there is limited room. As of today, there are about 300 GEO satellites in orbit. Because of their separation
requirement, they cannot be placed too close to each other because of radio-frequency interference. The existing GEO satellites fill most of the available slots.

Launching a satellite to a GEO is done in two steps. First the satellite is put in a geostationary transfer orbit (GTO) by the launcher. This orbit has its perigee at an altitude of 220 km and its apogee at geostationary altitude. The main reason for not launching a geostationary satellite directly to a GEO is to decrease the orbital life time of the last stage. The lower the last stage is dropped the faster it will reentry the atmosphere, thus limiting space debris. The second step is the apogee raising maneuver itself.

Using an EP thruster for the apogee-raising maneuver implies a slow, tedious transfer because of the low thrust of the EP thruster, compared to a chemical thruster using a Hohmann transfer where the velocity increase is gained at once. A low thrust transfer takes several months to complete, while a Hohmann transfer only requires a few days. However, it will require less propellant due to the much higher $I_{sp}$ of the EP thruster, thus decreasing the expenses for the launcher.

For more information on low thrust transfers to GEO using a HPEP thruster, see Romain Delanoë’s work on the HPEP project [5].

1.3 HPGP

The High Performance Green Propulsion (HPGP) system is a very good alternative to Hydrazine based propulsion systems. It has been developed by ECAPS, a subsidiary to the Swedish Space Corporation. ECAPS has developed several thrusters for the LMP-103S. The first, 1 N HPGP Thruster, Figure 1.1, is designed for orbit and attitude control of small satellites. It was flight proven in 2010 during the PRISMA mission [6]. ECAPS is currently also developing several other HPGP thrusters with 5, 22, 50 and 220 N thrust levels.

![Figure 1.1: The flight proven 1 N HPGP Thruster](image)

The Swedish Space Corporation developed “Prototype Research Instruments and Space Mission technology Advancement” (PRISMA), a two-spacecraft scientific mission with the main purpose of formation flight experiments. The mission consists of a small, simple satellite called “Target” and a larger satellite called “Main”. Target can be seen to the left, and Main to the right in Figure 1.2. Main has three propulsion systems, a HPGP system consisting of two 1 N thrusters and a hydrazine propulsion system consisting of six 1 N thrusters which allows it to maneuver. Main is also equipped with an experimental micro thruster cold-gas system [7]. This allowed for a back-to-back performance comparison of HPGP vs. hydrazine.

The HPGP thruster uses a monopropellant based on ADN, called LMP-103S. ADN was discovered and put to use in The Soviet Union as early as in the 1970s, but was not known in the west until 1993 [8].
ADN is an energetic salt and oxidizer and it has a high solubility in water. Dissolved in water and mixed with fuels such as ammonia and methanol it becomes a liquid monopropellant. LMP-103S, developed by ECAPS with FOI consists of ADN, water, methanol and ammonia. Besides the simplified handling during fueling, LMP-103S is transport classed as UN 1.4S. This implies that it can be transported by air together with the satellite, which Hydrazine can not. It also has a reduced environmental impact, not being carcinogenic. Compared to hydrazine, LMP-103S has a 6% higher $I_{sp}$ which is a measurement of how fuel efficient the thruster is, 24% higher density which results in a better performance.

### 1.4 Electric Propulsion

Spacecraft propulsion is usually performed with conventional rockets which in most cases, use monopropellant fuel. This type of fuel is used due to simplicity and reliability compared to the bi-propellant or solid-fuel rockets used for launchers. These chemical rockets can deliver a high thrust but are not very fuel efficient compared to newer kinds of electrical propulsion.

Electrically powered spacecraft propulsion is not a new concept: the idea was born in the early 20th century [9], but it is relatively new to the space industry. Compared to conventional spacecraft propulsion, electrical propulsion delivers much lower thrusts, but does so with a much higher specific impulse. For orbital transfers, positioning, maneuvering etc. where a high thrust is not required, the electrical propulsion system is ideal for spacecraft propulsion.

EP uses different means to accelerate the propellant from Chemical Propulsion (CP). The EP thrusters can be divided into three main groups:

- **Electromagnetic**: Accelerating ions by the use of an electromagnetic field where the electric field is not aligned with the direction of the acceleration. Most electromagnetic thrusters use the Lorentz Force. Examples of Electromagnetic Thrusters: VASIMR, MPD Thruster, Helicon Double Layer Thruster and Electrodeless Plasma Thruster. $I_{sp}$ values for Electromagnetic thrusters have exceeded 12,000 seconds [10].

- **Electrostatic**: When the applied electric field is aligned with the direction of the acceleration, the thruster is considered Electrostatic. These thrusters use the Coulomb Force to accelerate ions. The Hall Effect thruster, for instance, is an electrostatic thruster.

- **Electrothermal**: Different means are used to increase the temperature of the chemical propellant. With the use of a nozzle, the extra energy in the propellant is converted into kinetic energy. Even though these thrusters have $I_{sp}$ values far from that of the previously mentioned EP thrusters, they are still much more efficient than any other chemical propulsion system.

An example of a electromagnetic plasma drive is the Electrodeless Plasma Thruster, developed by Mr. Grégory Emsellem. This thruster does not suffer from the main disadvantage most other Electromagnetic plasma drives suffer from: the degradation of the cathode, i.e electrode erosion.
1.5 Thesis overview

This thesis focuses on the development of the injector to the HPEP thruster. The development of the injector involves a design phase, a testing phase and a verification phase. Beyond this, the chemical reactions of vaporizing a liquid monopropellant, and the power needed to do this, are also investigated.

The following chapters presented in this thesis report are *HPEP Thruster*, *LMP-103S & Simulants*, *Power to vaporize*, *Injector Development*, *Test setup*, *Results & Conclusion*.

*HPEP Thruster* explains the working principle of the thruster, both with a schematic overview and then more in-depth. This chapter also details the constraints of the injector.

*LMP-103S & Simulants* focuses on the liquid monopropellant “LMP-103S”, the ionization of its species, the theoretical performance of the propellant and finally the simulants, used for the development of the injector.

*Power to vaporize* covers the theory of the energy or power needed to vaporize a liquid. A model for the vaporization & decomposition of the simulant salt is presented. The heat losses in the system are also investigated.

*Injector Development* first introduces the previous injector, the work on how to improve it and the reasons why a new injector had to be designed. Thereafter conceptual ideas are presented and finally the new injector is introduced.

*Test setup* explains the experimental setup for the testing of the injector. An overview is, first presented, followed by a more in-depth explanation of each essential system is explained more in depth.
Chapter 2

HPEP Thruster

The High Performance Electric Propulsion project, a cooperation between Elwing Corp. and OHB Sweden, aims at developing an EP thruster that uses a chemically energetic monopropellant instead of conventional EP propellant as Xenon. The single purpose is to equip a satellite with two different propulsion systems using a single propellant tank.

2.1 EIMPAcT

The Electrodeless Ionization Magnetized Ponderomotive Accelerator Thruster (EIMPAcT) is an EP device in which a high-frequency electromagnetic field together with a static magnetic field ionizes and accelerates atoms and molecules. The HPEP project is aiming at developing an EIMPAcT prototype able to use a chemically energetic propellant. One option is to use the LMP-103S which ECAPS use in their HPGP thrusters.

The electrodeless plasma thruster uses the magnetized ponderomotive force to accelerate ions with the help of electromagnetic fields. This fact distinguishes it from other electromagnetic thrusters using the Lorentz force as their main acceleration mechanism. To avoid the erosion problem, both electrons and ions have to be accelerated in the same direction, which is accomplished by using the Ponderomotive force.

2.2 Thruster Principle & Schematic Overview

The HPEP thruster has three stages. The first stage is the injector, and the two others are the ionization and acceleration stage of the EIMPAcT. An overview can be seen in Figure 2.1.

The liquid monopropellant enters the injector where it is vaporized. This gas then enters the ionization stage where a plasma is created using microwave generators and an ionization method called Electron Cyclotron Resonance. Ions and electrons with high enough energy escape a magnetic bottle into the acceleration stage of the thruster where the magnetized ponderomotive force acts on the electrons, pushing them out. The acceleration of the ions is a secondary effect because of the ambipolar field that is generated. These ions and electrons are ejected at very high velocities.

The EIMPAcT creates and accelerates the plasma inside a hollow quartz tube. It uses two microwave generators together with cavity resonators working as wave guides for the electromagnetic waves. One of the microwave generators has the purpose of ionizing the gaseous monopropellant while the other is generating the acceleration through the ponderomotive force. The EIMPAcT is also equipped with two magnets, these magnets create the magnetic bottle that only allows particles with high enough energy to leave the ionization stage. They also make sure the ponderomotive force acts in the right direction.
2.3 Ionization

Different plasma thrusters use different ways of ionizing the gas propellant, for example, a high current arc or electron bombardment. The EIMPaCT uses the electron cyclotron resonance (ECR) to ionize the propellant. The principle as it follows: a charged particle in a magnetic field gyrates around its guiding center with a frequency called the cyclotron frequency

\[ \omega_c \equiv \frac{|q|B}{m} \quad (2.1) \]

If the magnetic field is combined with a high frequency electromagnetic (EM) field with the same frequency, \( \omega_c \), the electrons will be continuously accelerated in their circular motion. Eventually the electron will gain such a velocity that it will ionize any atom or molecule in its way, release more electrons to be accelerated with ECR for further ionization. This will create new electrons and ultimately form a plasma.

The ECR ionization method is electrodeless, which means that it will not suffer from the heavy electrode erosion that other methods suffer from. The method requires a microwave generator to create the electromagnetic field. This method also require a permanent or solenoid magnet in order to generate a static magnetic field. The ionization stage of EIMPaCT has two magnets which create a magnetic bottle in order to only release ions with enough energy to pass through to the acceleration stage of the thruster.

2.4 Ponderomotive force

Considering the motion of an electron in the oscillating electric field and a magnetic field is the easiest way to derive this nonlinear force. The equation of motion for an electron is
Consider a spatially inhomogeneous electromagnetic wave-field oscillating at frequency $\omega$.

\[
\vec{E} = \vec{E}_0(\vec{x}) \cos \omega t
\]  

(2.3)

In first order, $\vec{v} \times \vec{B}$ may be neglected in Eq 2.2. Evaluate $\vec{E}$ at the initial position $x_0$

\[
m \frac{d\vec{v}_1}{dt} = -e \vec{E}(\vec{x}_0) \cos \omega t
\]  

(2.4)

\[
\vec{v}_1 = \frac{e}{m \omega} \vec{E}(\vec{x}_0) \sin \omega t
\]  

(2.5)

\[
\delta \vec{v}_1 = \frac{e}{m \omega^2} \vec{E}(\vec{x}_0) \cos \omega t
\]  

(2.6)

Looking at the second order, $\vec{E}(\vec{x})$ is expanded around $\vec{x}_0$

\[
\vec{E}(\vec{x}) = \vec{E}(\vec{x}_0) + (\delta \vec{r}_1 \cdot \nabla) \vec{E}|_{\vec{x}=\vec{x}_0} + ...
\]  

(2.7)

The $\vec{v}_1 \times \vec{B}$ is now added. $\vec{B}_1$ is given by Faraday’s Law

\[
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}
\]  

(2.8)

\[
\vec{B}_1 = -\frac{1}{\omega} \nabla \times \vec{E}|_{\vec{x}=\vec{x}_0} \sin \omega t
\]  

(2.9)

Thus, the second order part of Eq. 2.2 is then

\[
m \frac{d\vec{v}_2}{dt} = -e[(\delta \vec{r}_1 \cdot \nabla) \vec{E} + \vec{v}_1 \times \vec{B}_1]
\]  

(2.10)

Inserting Eqs. 2.5, 2.6, 2.9 into Eq. 2.10

\[
m \frac{d\vec{v}_2}{dt} = -e\left[(\frac{e}{m \omega} \vec{E} \cos \omega t \cdot \nabla) \vec{E} \cos \omega t - \frac{e}{m \omega} \vec{E} \sin \omega t \times -\frac{1}{\omega} \nabla \times \vec{E} \sin \omega t\right]
\]  

(2.11)

Averaging over time, the trigonometric functions are both equal to 1/2. And by definition

\[
\nabla \left( \frac{|\vec{E}|^2}{2} \right) \equiv (\vec{E} \cdot \nabla) \vec{E} + \vec{E} \times (\nabla \times \vec{E})
\]  

(2.12)

Thus, the Ponderomotive force can be expressed as

\[
\vec{f} = -\frac{e^2}{4m \omega^2} \nabla \vec{E}^2
\]  

(2.13)

This is the force on a single electron. Although the force acts mainly on the electrons because the force is inversely proportional to the mass of the particle, the ponderomotive force is transmitted to the ions through the ambipolar field that is generated from the charge separation when the electrons are accelerated faster. This results in both electrons and ions having the same mean velocity.

Using the expression for plasma frequency $\omega_p$,

\[
\omega_p^2 = \frac{n_0 e^2}{m_0}
\]  

(2.14)

Eq. 2.13 can be rewritten as
Chapter 2. HPEP Thruster

2.4. Ponderomotive force

\[
\vec{f} = -\frac{\omega_p^2}{2n_0\omega^2} \nabla \varepsilon_0 E^2 \frac{2}{2}
\]  

(2.15)

Considering the total force on a plasma, and not just the force on a single electron. Eq. 2.15 can be multiplied by the plasma density \(n_0\)

\[
\vec{F} = -\frac{\omega_p^2}{2\omega^2} \nabla \varepsilon_0 E^2 \frac{2}{2}
\]  

(2.16)

The \(\varepsilon_0 E^2 \frac{2}{2}\) term represents the electromagnetic energy density in an electric field. This makes it clear that the ponderomotive force is related to an EM energy density gradient. The sign in Eq. 2.15 shows that the force is acting towards a region with lower EM energy density.

However, having an area with a higher EM energy density implies that there is one area on each side with lower EM energy density. Thus, the ponderomotive force would simply push the plasma out from the higher EM energy density area. This is shown in Figure 2.2.

![Figure 2.2: The higher and lower EM density areas creating the ponderomotive force](image)

To control this, and push the plasma in the right direction, a magnetic field is added. When a static magnetic field is added, the ponderomotive force changes into

\[
\vec{F} = -\nabla \left( \frac{\omega_p^2}{2\omega(\omega - \omega_c)} \frac{\varepsilon_0 E^2}{2} + \frac{\mu B}{2} \right)
\]  

(2.17)

and \(\mu\) is the magnetic moment, which is one of the adiabatic invariants and is a quantity of the force that a magnetic field can have on an electric current. Thus, both the static magnetic field, the magnitude of the oscillating EM field and the plasma frequency are space dependent, while all the other parameters are constant. Applying the product rule to Eq. 2.17 gives

\[
\vec{F} = -\frac{\omega_p^2}{2\omega(\omega - \omega_c)} \nabla \left( \frac{\varepsilon_0 E^2}{2} + \frac{1}{2} \nabla \frac{1}{\omega - \omega_c} - \frac{\mu}{2} \nabla B \right)
\]  

(2.18)

If the EM energy density and the magnetic field only varies along the x-axis, Eq. 2.18 can be expressed as

\[
F = -\left( \frac{\omega_p^2}{2\omega(\omega - \omega_c)} \frac{\partial \varepsilon_0 E^2}{\partial x} + \frac{\omega_p^2}{2\omega(\omega - \omega_c)^2} \frac{\varepsilon_0 E^2}{2} \frac{\partial \omega_c}{\partial x} - \frac{\mu}{2} \frac{\partial B}{\partial x} \right)
\]  

(2.19)
This equation is split in three parts, showing three different forces acting on the plasma. The sum of the forces depends on the change in EM energy density, the change in the magnetic field and whether the cyclotron frequency is higher or lower than the EM wave frequency.

Since the cyclotron frequency is dependent on the magnetic field $B$, there is a certain magnetic field $B_{\text{resonance}}$ that gives a cyclotron frequency equal to the frequency of the EM waves. This also implies that $\frac{\partial \omega_c}{\partial x}$ has the same sign as $\frac{\partial B}{\partial x}$. In Table 2.1 all the eight different possibilities are shown and what sign the total resulting magnetized ponderomotive force has.

<table>
<thead>
<tr>
<th>case</th>
<th>$\frac{\partial \varepsilon E^2}{\partial x}$</th>
<th>$\omega - \omega_c$</th>
<th>$B - B_{\text{res}}$</th>
<th>$\partial B/\partial x$</th>
<th>$F_1$</th>
<th>$F_2$</th>
<th>$F_3$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>?</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>?</td>
<td>+</td>
</tr>
<tr>
<td>5</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>6</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>7</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>?</td>
</tr>
<tr>
<td>8</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 2.1: Different conditions resulting in different signs on each of the three acting forces of the magnetized ponderomotive force

Only case 2 and 8 in Table 2.1 result in all three forces being positive. In case 2, the change in EM energy density is positive, $B$ is stronger than $B_{\text{res}}$ and the magnetic field intensity gradient is negative. In case 8, the change in EM energy density is negative, $B$ is weaker than $B_{\text{res}}$ and the magnetic field intensity gradient is still negative. Cases 1, 4, 6 and 7 might turn out to have a positive total force as well, all depending on the relations between the forces.

From this, several conclusions can be drawn. To control the direction of the Ponderomotive force, the high frequency EM oscillations have to be combined with a static magnetic field. This magnetic field must be stronger than $B_{\text{res}}$ if the plasma is to accelerate into the high EM energy density area, and weaker than $B_{\text{res}}$ if the plasma is to accelerate away from the high EM energy density area. Such a case is shown in Figure 2.3 where the direction of the ponderomotive force is controlled.

![Image of Figure 2.3](image-url)
2.5 Injector

The EIMPAcT needs the propellant in a gaseous state for the ionization and acceleration part of the thruster. Since the monopropellant is liquid, the injector has the single purpose to vaporize it in a continuous flow into the EIMPAcT. This has to be done without decomposing the ADN, meaning that the temperature of the gas should be kept below 180°C [11].

The injector design also has a few other criteria. These criteria are presented below:

- Sufficient heat transfer to evaporate the required mass flow
- Low thermal losses (relatively)
- Low thermal inertia (fast warm up)
- Low weight
- Chemically resistant
- Temperature tolerant
Chapter 3

LMP-103S and Simulants

3.1 LMP-103S

The LMP-103S, developed between ECAPS and FOI [12] is an Ammonium DiNitramide (ADN) based monopropellant. The mass ratio is displayed in Table 3.1. The real composition of LMP-103S is confidential.

The LMP-103S was developed as a green alternative to ammonium perchlorate (AP) and Hydrazine which are both very toxic and expensive to handle because of hazardous reasons.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADN</td>
<td>60-65</td>
</tr>
<tr>
<td>Methanol</td>
<td>15-20</td>
</tr>
<tr>
<td>Ammonia</td>
<td>3-6</td>
</tr>
<tr>
<td>Water</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 3.1: LMP-103S [1]

LMP-103S is both highly flammable and explosive [1], partially because of the methanol but also because the ADN decomposes at high temperatures with an exothermal reaction, releasing even more heat. These higher temperatures have to be avoided for safety reasons.

3.2 Ionization of LMP-103S

A computational study of the breakdown of ADN and the reactions of the breakdown products with focus on ionization potentials and cross-sections was performed at KTH during the spring of 2012 [2]. The study showed that ADN can either be vaporized in the injector as ADN(g) or as the acid base pair HDN and NH₃. The ADN/HDN ratio is temperature dependent [13]. It is shown that for 160°C and low pressure, roughly 92.5% of the ADN is vaporized while the rest is dissociated into HDN(g) and NH₃(g).

The ADN ion will instantly dissociate into a DiNitramide (DN) radical and a NH⁺ ion when ionized. Other reactions are less likely. This reaction is endothermic with 17 kJ/mol. The DN radical is then ionized to a DN⁺ ion. Thus the complete ionization of ADN results in

\[
\text{ADN}^+ \rightarrow \text{DN}^+ + \text{NH}_3^+ \rightarrow \text{DN}^+ + \text{NH}_4^+ + \text{N}_2 \quad (3.1)
\]

The breakdown of the DN⁺ ion can lead to N₂O, O₂ and NO⁺ but this reaction has a barrier of 75 kJ/mol and can therefore be seen as very unlikely [2].
Chapter 3. LMP-103S and Simulants 3.3. Thrust to Power ratio

The HDN ion has several pathways for the breakdown. However, one has a much lower barrier of only 15 kJ/mol, resulting in a HNNO\(_2\) radical and a NO\(_2^+\) ion with an 80 kJ/mol exothermic reaction. The HNNO\(_2\) radical is then ionized to a very stable HNNO\(_2^+\) ion [2]. Thus the complete ionization of HDN results in

\[
\text{HDN}^+ \rightarrow \text{HNNO}_2^+ + \text{NO}_2^+ \rightarrow \text{HNNO}_2^+ + \text{NO}_2^+ \quad (3.2)
\]

The other pathways are very unlikely because of a 145 kJ/mol barrier.

The amount of each species in the gaseous LMP-103S leaving the injector, assuming a temperature of 160°C, in Table 3.2

<table>
<thead>
<tr>
<th>Species</th>
<th>Mole%</th>
<th>Mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADN</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>HDN</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>NH(_3)</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>CH(_4)O</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>H(_2)O</td>
<td>27</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.2: LMP-103S in gaseous state 160°C [2]

In Table 3.3 the gaseous LMP-103S, assuming a complete breakdown of ADN and HDN after ionization, is shown. Note how most of the ADN has decomposed into the quite heavy molecule of DN.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mole%</th>
<th>Mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN(^+)</td>
<td>19</td>
<td>51</td>
</tr>
<tr>
<td>NH(_4^+)</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>HNNO(_2^+)</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>NO(_2^+)</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>CH(_4)O(^+)</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>H(_2)O(^+)</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>NH(_3^+)</td>
<td>13</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 3.3: LMP-103S immediately after ionization, 160°C [2]

3.3 Thrust to Power ratio

A propulsion system is characterized by how much thrust per unit of mass propellant is given, i.e. the specific impulse, \(I_{sp}\). Electric propulsion excels in this fuel efficiency property compared to chemical propulsion having up to 30 times better \(I_{sp}\) values.

Chemical propulsion systems only use a small amount of electrical power to fire the thrusters while the main energy is given though the chemical combustion. Electric propulsion systems do not have this stored chemical energy, thus the high power has to be provided by the spacecraft. This can be seen as a downside for EP. Especially if a heavy power supply has to be carried on board with the single purpose of delivering power to the thruster.

So when comparing performance between EPS, not only is the \(I_{sp}\) used, but a Thrust-to-Power ratio where the electrical efficiency is rated is also used. This parameter is not only dependent on the thruster but on the propellant as well. Hence, the thrust-to-power ratio is derived and evaluated.

The energy used in the ionization stage per molecule can be expressed as
3.3. Thrust to Power ratio

\[ E_p = \frac{E_{\text{ion}}}{\alpha_{\text{ion}}} \]  

(3.3)

where \( E_{\text{ion}} \) is the ionization potential and \( \alpha_{\text{ion}} \) is the ionization efficiency, ranging between 0 and 1. All losses in the ionization chamber can be taken into account in the \( \alpha_{\text{ion}} \) coefficient.

The energy used in the acceleration stage can be expressed as

\[ E_k = \frac{1}{2} m V_e^2 \]  

(3.4)

where \( V_e \) is the exhaust velocity and \( m \) is the mass of a considered ion.

If the exhaust velocity is expressed in specific impulse

\[ V_e = g_0 I_{sp} \]  

(3.5)

where \( g_0 \) is the acceleration at the Earth’s surface, and \( I_{sp} \) is the specific impulse. Then the total energy used in an EP thruster to accelerate an ion to a specific velocity is

\[ E_{\text{tot}} = \frac{E_{\text{ion}}}{\alpha_{\text{ion}}} + \frac{1}{2} m g_0^2 I_{sp}^2 \]  

(3.6)

expressing this equation as power gives

\[ P = \frac{E_{\text{tot}} \dot{m}}{m} = \frac{E_{\text{ion}} \dot{m}}{\alpha_{\text{ion}} m} + \frac{1}{2} \dot{m} g_0^2 I_{sp}^2 \]  

(3.7)

The thrust of a rocket is related to the exhaust velocity \( V_e \) and the mass flow, \( \dot{m} \).

\[ T = V_e \dot{m} = g_0 I_{sp} \dot{m} \]  

(3.8)

A ratio between the thrust and the power can therefore be expressed as, by dividing equation 3.8 by equation 4.1

\[ \frac{T}{P} = \frac{g_0 I_{sp}}{\frac{E_{\text{ion}}}{\alpha_{\text{ion}} m} + \frac{1}{2} \dot{m} g_0^2 I_{sp}^2} \]  

(3.9)

Three conclusions can be drawn from equation 3.9. The \( T/P \) ratio is a function of \( I_{sp} \), which is variable for the HPEP thruster. The ratio also depends on the propellant - how easy it is to ionize and what mass it has. A higher mass giving a higher \( T/P \) ratio. Finally, the \( T/P \) depends on the ionization efficiency, which is itself dependent on the ionization process.

The ionization efficiency of the EIMPAcT was measured to 46.2% during a test with Argon performed by Onera [14]. However, since the molecules of LMP-103S are much larger they will have a larger ionization cross section. Because of this a 60% ionization efficiency is used.

In Figure 3.1, two different results from the ionization of LMP are compared to Xenon and Argon for the thrust to power ratio. The “ideal LMP-103S” is where the ADN and the HDN have been ionized but not decomposed into their bi-products. The “LMP-103S” curve represents a breakdown of all ADN and HDN molecules. Thus, both a best and worst case are represented. It should be noted that all propellant curves in Figure 3.1 are based on an ionization efficiency of 60%, which should actually be lower, at least for Argon.

Even though the breakdown of HDN has a 80 kJ/mol exothermal reaction, this reaction should not heat the gaseous LMP-103S due to the fact that the breakdown of ADN has a 17 kJ/mol endothermal reaction and that there is 15 times as much ADN as HDN. Thus, no thermal expansion of the gas is expected.
3.4 Simulants

A safer approach on developing the thruster for LMP-103S is to use a non-flammable, less toxic and cheaper mixture instead of LMP-103S for testing. This way, more extensive testing can be done in less costly facilities and under much simpler conditions.

Four “simulants” to ADN were suggested [15]:

- **Ammonium Nitrate** because it is a by-product of the decomposition of ADN and sharing the exothermic properties of decomposition. However, Ammonium Nitrate has a melting point of 169°C compared to 91°C of ADN. The melting point gives a good estimate of the decomposition temperature. The Ammonium Nitrate was not optimal from this perspective.

- **Ammonium Acetate** however, has a melting point at 114°C and it decomposes to acetamide, ammonia, acetic acid and water, none of which are very harmful.

- **Ammonium Trifluoroacetate** has its melting point of about 124°C. It decomposes to a stronger acid and is therefore more similar to HDN. The issue with Ammonium Trifluoroacetate is the compatibility of the trifluoroacetic acid to the injector and the rest of the test setup.

- **Ammonium Formate** melts at 116°C. The acid is stronger than acetic acid from Ammonium Acetate but much weaker than trifluoroacetic acid.

Out of the four considered simulants, most attention was payed to Ammonium Acetate and Ammonium

<table>
<thead>
<tr>
<th>Species</th>
<th>Molar Mass [g/mol]</th>
<th>IP [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xe</td>
<td>131.29</td>
<td>12.13</td>
</tr>
<tr>
<td>Ar</td>
<td>39.95</td>
<td>15.8</td>
</tr>
<tr>
<td>DN</td>
<td>106.02</td>
<td>11.8</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>18.04</td>
<td>11.5 (ADN)</td>
</tr>
<tr>
<td>HNNO₂</td>
<td>61.02</td>
<td>11.2</td>
</tr>
<tr>
<td>NO₂</td>
<td>46.01</td>
<td>12.5 (HDN)</td>
</tr>
<tr>
<td>CH₄O</td>
<td>32.04</td>
<td>10.9</td>
</tr>
<tr>
<td>H₂O</td>
<td>18.01</td>
<td>12.62</td>
</tr>
<tr>
<td>NH₃</td>
<td>17.03</td>
<td>10.07</td>
</tr>
</tbody>
</table>

Table 3.4: Ionization potential and molar mass of the decomposition products of LMP-103S after vaporization and subsequent ionization

Figure 3.1: Thrust to power ratio of different propellants
Nitrate. However, Swedish laws state that Ammonium Nitrate may not be heated to a temperature where it decomposes. Approvals are needed to use it and because of the risk of fire or even a detonation, Ammonium Nitrate was discarded.

Before starting with any simulant, the injector is to be tested with water in order to determine its characteristics, i.e. what temperatures it reaches to boil the continuous flow of water, how steady the flow is and just to test the whole setup. The water tests are also used to create a theoretical model for the power losses. Different tests result in different circumstances, for instance different mass flows through the injector results in different humidities in the vacuum chamber.

Tests here aim to find the power needed to vaporize a certain mass flow of a mixture, depending on the simulant composition, how much the temperature of the injector increases with power from the power where all of the flow is vaporized. This is done for four different flow rates: 100 mg/s, 90 mg/s, 50 mg/s and 10 mg/s. The purpose is to see how the injector behaves if there for some reason would be a change in power or possibly even a choke in the monopropellant flow. Because of the latter reason, thermal choke tests are also performed.

Continuing from water, two binary mixtures of Ammonium Acetate (AA) and water are made. Since the true composition of LMP-103S is confidential, the whole range showed in Table 3.1 is considered through two different concentrations: one “high end”, meaning a molar ratio corresponding to the high mass ratio of ADN of LMP-103S, and one “low end” with a molar ratio equal to the low mass ratio. This implies that the “high end” mixture is low on water, while the “low end” is high on water.

From the binary mixtures, ternary mixtures are considered before moving on to full mixtures. However, since the full mixture is of much greater importance, the ternary mixtures is omitted, unless the full mixtures are non successful.

Even though ADN has a higher solubility than AA in water, it is possible to solve as much AA in a mixture of water, ammonia and methanol to acquire the same molar ratios as for both the high- and low end of the LMP-103S.

In Table 3.5 both the high- and low end of LMP-103S, the binary and the full mixtures are shown in mass ratios and in molar ratios. Note that the molar ratios are not an exact match, but since no good tools are available for the actual making of the mixtures, there is little point in high accuracy. It should also be noted that the “high end” of LMP-103S has 5% of Ammonia instead of 6% as presented in Table 3.1. This is simply because Ammonia is added with Ammonium Hydroxide with a 30% mass fraction of Ammonia. This implies that only 5% Ammonia could be added.

### 3.4.1 Making the simulant

The full simulant mixture was made in four steps. First, the correct amount of ammonium acetate was measured on a scale and then added to the bottle, seen in Figure 3.2a. The water is then added, saving the volatile chemicals until last: ammonia and methanol were each measured on the scale and then added to the mixture so that the bottle could be closed. The non-dissolved newly made mixture is seen in Figure 3.2b

The mixture’s temperature quickly drops as the Ammonium Acetate dissolves in the water and methanol. Due to the temperature drop, the mixture either becomes saturated or it just becomes more difficult to dissolve what remains of the salt. Because of this, the mixture is left to rest for half a day so that the mixture return to room temperature and so that all of the Ammonium Acetate is dissolved.
### Table 3.5: Composition of LMP and the binary & full mixtures of the simulant

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Molecular Formula</th>
<th>Molar Mass [g/mol]</th>
<th>Mass [%]</th>
<th>Mole [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LMP-103S</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADN</td>
<td>NH₃HN(NO₂)₂</td>
<td>124.06</td>
<td>65/60</td>
<td>26.24/20.58</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₄O</td>
<td>32.04</td>
<td>20/15</td>
<td>31.26/19.93</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>17.03</td>
<td>5/3</td>
<td>14.70/7.50</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>18.01</td>
<td>10/22</td>
<td>27.80/21.99</td>
</tr>
<tr>
<td><strong>Binary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA</td>
<td>C₂H₃O₂NH₄</td>
<td>77.08</td>
<td>53.5/48</td>
<td>21.19/17.74</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₄O</td>
<td>32.04</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>17.03</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>18.01</td>
<td>46.5/52</td>
<td>78.81/82.26</td>
</tr>
<tr>
<td><strong>Full</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA</td>
<td>C₂H₃O₂NH₄</td>
<td>77.08</td>
<td>53.5/48</td>
<td>26.17/20.43</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH₄O</td>
<td>32.04</td>
<td>26.5/19.5</td>
<td>31.18/19.96</td>
</tr>
<tr>
<td>Ammonia</td>
<td>NH₃</td>
<td>17.03</td>
<td>6.5/4</td>
<td>14.39/7.70</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>18.01</td>
<td>13.5/28.5</td>
<td>28.26/51.91</td>
</tr>
</tbody>
</table>

(a) Salt stuffed into the bottle  
(b) Mixture not fully dissolved

Figure 3.2: Making of the full mixture
Chapter 4

Power to vaporize

4.1 Theory

In order to know what power is needed to vaporize a mass flow of a certain mixture, a theoretical model is needed, as well as data for molar mass, melting point, boiling point, fusion enthalpy, vaporization enthalpy, decomposition enthalpy and heat capacities (in different states).

The theoretical model, in general, has to consider the heating from a liquid state up to the boiling point, the boiling itself, and heating of the gas up to a certain temperature. Depending on the chemical itself, these values will change. A dissolved salt for instance is still considered to be in a solid state and it will have to melt first or go directly to a gaseous state. Ammonium Acetate is known to decompose for higher temperatures at standard pressure. However, since the injector is meant to work in vacuum, Ammonium Acetate might not decompose but vaporize instead.

The general model consists of four parts

\[ P = \frac{\dot{m}}{M} \left( C_{p,m(l)}(T_{\text{vap}} - T_{\text{in}}) + \Delta H_{\text{vap}} + C_{p,m(g)}(T_{\text{end}} - T_{\text{vap}}) \right) + P_{\text{losses}} \]  

where the first part corresponds to heating the mass flow to the point where it starts to vaporize, the second part corresponds to the vaporization itself and the third part corresponds to the additional heating of the gas flow. The fourth and last part corresponds to the heat losses: radiative, conductive and convective losses.

Most of the information found for the chemicals considered, Ammonium Acetate, Methanol, Water and Ammonia, are based on standard pressure. Since this is not the case, some assumptions and calculations were made. While the melting point is assumed not to change much with pressure, the boiling point changes a lot: it is commonly known that boiling points tends to decrease with a decrease in pressure. The Clausius-Clapeyron relation [16]

\[ T_B = \left( \frac{R \ln(P)}{\Delta H_{\text{vap}}} + \frac{1}{T_0} \right)^{-1} \Rightarrow T_{\text{vap}}(P) = \left( \frac{1}{T_B} - \frac{R \ln(P)}{\Delta H_{\text{vap}}} \right)^{-1} \]  

is an expression relating pressure and boiling point. This relation is used to calculate the boiling point for all the chemicals in the simulant mixture.

4.2 Vaporization of Ammonium Acetate

Even though the purpose is not to decompose the Ammonium Acetate, it cannot be vaporized without decomposition in standard pressure. Because of this, and lack of proof that it is possible to vaporize, only decomposition of Ammonium Acetate is considered.
Chapter 4. Power to vaporize

4.3. Vaporization of Ammonium DiNitramide

An earlier experiment [17] proved that the decomposition of Ammonium Acetate starts at a temperature of 326 K. However, most of the decomposition takes place at temperatures around the melting point at 387 K, or above. Because of the complexity of the decomposition, this simplified theoretical model assumes that the whole decomposition goes from a solid state into a gaseous state. This means that the melting and vaporization phases are not considered at all. The thermodynamics does not depend on which way a reaction goes, only the initial and final state, only the decomposition from a solid salt to the product gases is considered.

According to Erday et al. [18] the decomposition of Ammonium Acetate starts at temperatures above 60°C, where ammonia is lost and only acetic acid is left

\[
\text{C}_2\text{H}_4\text{O}_2\text{NH}_4(\text{s}) \rightarrow \text{NH}_3(\text{g}) + \text{C}_2\text{H}_4\text{O}_2(\text{g})
\]  

(4.3)

At higher temperatures, about 150°C, acetamide and water are formed

\[
\text{C}_2\text{H}_3\text{O}_2\text{NH}_4(\text{s}) \rightarrow \text{C}_2\text{H}_5\text{NO}(\text{l}) + \text{H}_2\text{O}(\text{g})
\]  

(4.4)

The enthalpy change of decomposition is found by looking at the enthalpy of formation for each species and calculating the difference, Table 4.1.

<table>
<thead>
<tr>
<th>Molecular Formula</th>
<th>(\Delta f H) (kJ · mol(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{C}_2\text{H}_4\text{O}_2\text{NH}_4(\text{s}))</td>
<td>-587</td>
</tr>
<tr>
<td>(\text{NH}_3(\text{g}))</td>
<td>-45.9</td>
</tr>
<tr>
<td>(\text{C}_2\text{H}_4\text{O}_2(\text{g}))</td>
<td>-432.2</td>
</tr>
<tr>
<td>(\text{C}_2\text{H}_5\text{NO}(\text{l}))</td>
<td>-238.3</td>
</tr>
<tr>
<td>(\text{H}_2\text{O}(\text{g}))</td>
<td>-241.8</td>
</tr>
</tbody>
</table>

Table 4.1: Standard enthalpy of formation of compounds in Reaction 4.3 and 4.4 [3, 4]

The enthalpy change of reaction 4.3 is then calculated as

\[
\Delta H = \Delta f H(\text{C}_2\text{H}_4\text{O}_2(\text{g})) + \Delta f H(\text{NH}_3(\text{g})) - \Delta f H(\text{C}_2\text{H}_3\text{O}_2\text{NH}_4(\text{s})) = 108.9 \text{kJ} \cdot \text{mol}^{-1}
\]  

(4.5)

This result is in order with the experimentally obtained value of \(\Delta H = 110 \pm 4 \text{ kJ mol}^{-1}\) taken from Jaffe et al. [19].

The enthalpy change of reaction 4.4 is also calculated as

\[
\Delta H = \Delta f H(\text{H}_2\text{O}(\text{g})) + \Delta f H(\text{C}_2\text{H}_5\text{NO}(\text{l})) - \Delta f H(\text{C}_2\text{H}_3\text{O}_2\text{NH}_4(\text{s})) = 106.9 \text{kJ} \cdot \text{mol}^{-1}
\]  

(4.6)

Both these reactions are endothermic and because of the fact that they are close to equal in enthalpy change, the ratio is not of greater importance. In the model, a ratio of 1/1 is adopted, partially because the ratio is not of great importance but also because the temperature where Reaction 4.4 occurs in vacuum is unknown.

Under normal conditions, the solid/liquid Ammonium Acetate would decompose into liquid Acetamide, but because of very low pressures in a vacuum, the boiling point for Acetamide should be below the melting point of the Ammonium Acetate, which is assumed not to have changed from normal conditions. Therefore all the products from the decomposition should evaporate instantly. Thus, a temperature just above the melting point for AA should be sufficient for a total decomposition into a gaseous state.

### 4.3 Vaporization of Ammonium DiNitramide

Mebel et al. [20] determined through their research that ADN could not exist in vapor form because it would decompose before vaporizing. However, Shmakov et al. [13] were able to vaporize the salt without decomposing it, under low pressure. Because of their research, ADN is assumed only to partially break down into \(\text{NH}_3\) and HDN.

\[
\text{NH}_3 \cdot \text{HN(NO}_2)_2(\text{g}) \rightarrow \text{NH}_3(\text{g}) + \text{HN(NO}_2)_2(\text{g})
\]  

(4.7)
Chapter 4. Power to vaporize

4.4 Calculated power

According to Tompa et al. the molar heat capacity of the ADN is 161.28 J/(mol·K) [11], and in a study performed by Swedish FOI, Östmark et al. [21] determined the solid heat capacity of ADN to be 223.31 J/(mol·K).

Östmark et al also determined the enthalpy change of fusion, \( \Delta H_{\text{fus}} \) to be 16.13 kJ/mol.

No data for ADN heat capacity in liquid state could be found. However, Osman et al. [22] showed that the heat capacity of Ammonium Acetate and Ammonium Nitrate changes only by a few percent when the state changes from solid to liquid. Because of this, the 161.28 J/(mol·K) value is also used for the liquid state.

Shmakov et al. experimentally determined the enthalpy change of vaporization for ADN to be 147.0-155.4 kJ/mol which verifies the earlier theoretically predicted 155.4±12.6 kJ/mol, by Mebel et al.

The NRFP study [2] showed that at a temperature of 160°C, 7.5 mol% of all the initial ADN would decompose into HDN. Shmakov et al. showed that this reaction is exothermal and releases 50.4-58.8 kJ/mol depending on isomers.

Having a complete model for how ADN vaporizes in the injector, the power needed for vaporization can be determined.

### 4.4 Calculated power

Using the model, minimum power \( P_{\text{min}} \) could be calculated for all mixtures and flow rates, see Table 4.2. These powers are the ideal powers, i.e without losses. Note that the powers are linearly dependent on the mass flow rate.

<table>
<thead>
<tr>
<th>Flow [mg/s]</th>
<th>100</th>
<th>90</th>
<th>50</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_2O ) [W]</td>
<td>230.4</td>
<td>207.4</td>
<td>115.2</td>
<td>23.04</td>
</tr>
<tr>
<td>Binary (Hi) [W]</td>
<td>184.0</td>
<td>165.6</td>
<td>92.0</td>
<td>18.4</td>
</tr>
<tr>
<td>Binary (Low) [W]</td>
<td>189.0</td>
<td>170.1</td>
<td>94.5</td>
<td>18.9</td>
</tr>
<tr>
<td>Full (Hi) [W]</td>
<td>145.2</td>
<td>130.6</td>
<td>72.6</td>
<td>14.5</td>
</tr>
<tr>
<td>Full (Low) [W]</td>
<td>161.3</td>
<td>145.2</td>
<td>80.7</td>
<td>16.1</td>
</tr>
<tr>
<td>LMP-103S (Hi) [W]</td>
<td>158.8</td>
<td>142.9</td>
<td>79.4</td>
<td>15.9</td>
</tr>
<tr>
<td>LMP-103S (Low) [W]</td>
<td>171.9</td>
<td>154.7</td>
<td>86.0</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Table 4.2: \( P_{\text{min}} \) for each mixture and flow rate

However, there are always losses in the system, and these have to be accounted for in order to know how much power is needed for complete vaporization.

### 4.5 Losses

The difference between the ideal power to vaporize a continuous mass flow of a mixture and the real power needed by the injector to vaporize it is, besides the fact that the model is not fully accurate, that there are losses in the system.

There are three different thermal heat transfers, i.e losses, between the injector and the surrounding environment: radiative, conductive and convective. These have to be considered because they are far from negligible.
4.5.1 Radiative

The motion of charged particles in matter generates electromagnetic radiation. This is referred to as thermal radiation. The higher temperature the matter has, the more it will radiate.

The power of the thermal radiation is, for a “grey body”, defined with Stefan-Boltzmann’s law

\[ P = \sigma A e \varepsilon T^4 \] (4.8)

where \( \sigma \) is the Stefan-Boltzmann constant, \( A e \) the total surface of the emitting body and \( \varepsilon \) the emissivity coefficient. The power is a function of the absolute temperature raised to the power of four. This means that at higher temperatures, the emitting body will radiate significantly more than for a lower temperature.

However, the emitting body will not only radiate away heat, but also absorb radiation from the environment. This absorbed power is expressed as

\[ P = R \alpha A_{ill} \] (4.9)

where \( R \) is the radiation per area, \( \alpha \) is the absorption and \( A_{ill} \) is the radiated area. The absorption coefficient is equal to the emissivity coefficient for a grey body assumption. Because the injector is considered to be opaque, the radiation is either absorbed or reflected.

This implies that the electromagnetic radiation will bounce back and forth between the injector and the surrounding test environment. For further reference, the effective emissivity coefficient \( \varepsilon_{eff} \) is determined through tests where the coefficient fulfills the equation at a thermal steady state.

Thus, equation 4.8 is rewritten as

\[ P = \sigma A e \varepsilon_{eff} T^4 \] (4.10)

4.5.2 Conductive

The conductive heat transfer

\[ P = k A L \Delta T \] (4.11)

is a function of the material parameter thermal conductivity \( k \), the contact area \( A \), the length of the conductive path and the difference in temperature, \( \Delta T \), between the conductive path.

In this work, the considered pathways for the thermal conduction are through the mounting of the injector, the fuel pipe and the thermocouples attached to the body. The total area is approximately 9 mm\(^2\), the length 5 cm and the temperature difference is the difference between the average injector body temperature and the temperature of the vacuum chamber, which is room temperature. The thermal conductivity of stainless steel is 18-24 W/(m·K) for temperatures around room temperature [23].

4.5.3 Convective

The convective heat transfer can be described by Newton’s law of cooling

\[ P = h A \Delta T \] (4.12)

where \( h \) is the convective heat transfer coefficient (assumed constant with temperature), \( A \) is the surface area and \( \Delta T \) the temperature difference between the body and the ambient gas temperature.

The convective heat transfer coefficient is a very complex parameter simply because it depends on the material, the thermal conductivity of the fluid, geometric properties and many more parameters such as...
Nusselt number, Reynolds number, Prandtl number et cetera.

Instead of calculating this coefficient, it was determined through experiments, since it depends on the humidity of the residual gas inside the vacuum chamber. A higher mass flow through the injector will result in a higher humidity, and in turn a higher convective heat transfer coefficient.

### 4.5.4 Investigation

Two experiments are executed without any flow and for two different power levels: 20 and 30 W (Figure 4.1) under vacuum. Temperature is measured at six points on the injector at thermal equilibrium as well as the residual gas temperature in the vacuum chamber and the chamber wall temperature. Measuring gas temperature with a thermocouple in low pressure is not very reliable, thus the residual gas temperature is assumed to have the same temperature as the temperature wall.

![Figure 4.1: Temperature curve 30 W, where TC1-6 is the temperature of the injector body](image)

The conductive heat transfer is estimated and thought to be lost through the fuel inlet pipe, the mounting and the six thermocouples. This gives an equation system

\[
\begin{bmatrix}
P_t - \frac{kA}{L} \Delta T \\
P_y - \frac{kA}{L} \Delta T
\end{bmatrix} = \begin{bmatrix}
T^4 \sigma A_{inj} \\
T^4 \sigma A_{inj}
\end{bmatrix} \times \begin{bmatrix}
\varepsilon_{eff} \\
h
\end{bmatrix}
\]

which can be used to determine the radiative and convective heat losses. \( \varepsilon_{eff} \) is the effective emissivity coefficient, \( h \) is the convective heat transfer coefficient, \( \sigma \) is Stefan–Boltzmann constant, \( A_{inj} \) is the total surface area of the injector and \( \frac{kA}{L} \Delta T \) is the conductive heat transfer.

This gives a good estimation of how much heat is lost through radiation and convective heat transfer, respectively. The results indicated an effective emissivity coefficient close to 0.5 and a convective heat transfer coefficient of 1.6 W/(m\(^2\)K), which is reasonable for the pressure of 30 mbar during the experiment.

The convective heat loss depends on the flow rate through the injector, resulting in different humidities and a slightly different pressure inside the chamber. Since the emissivity coefficient is by now known, the difference between the ideal model including the conductive and radiative losses, and the actual power needed to vaporize the flow can be determined to be the convective heat loss.

Thus, the convective heat transfer coefficient can be solved for, for each test with water for different flow rates. Using these tests with water gives and idea of how large the convective heat transfer coefficient is.

Having accounted for all the losses, the theoretical model is well-adapted to determine the power needed to evaporate any simulant mixture, at any flow.
Chapter 5

Injector development

5.1 Injector One

The first LMP-103S injector was designed at OHB Sweden during the spring of 2011. It is a stainless steel cylinder enclosing a cartridge heater as seen in Figure 5.1. The cylinder has seven small holes drilled through it allowing fluid to flow through. This design gives a rather compact injector because of the high watt density compared to rope heaters or tape heaters that were also considered at the time.

The cartridge heater inside the injector is manufactured by Omega and can deliver a power of 400 W. It has a diameter of 6.4 mm and a length of 76.2 mm. Its small size and high power make it suitable as the cartridge heater is the limiting factor for the size of the injector.

![Injector One](a) Injector One

![400W Omega Cartridge heater](b) 400W Omega Cartridge heater

Figure 5.1: Injector One with the heating element

This injector worked well for low flow rates with water. When the mass flow was set to 100 mg/s, some liquid water exited the injector in the form of droplets. The injector was modified, by adding a “cap” at the end of the injector, see Figure 5.2. This cap increased the heat transfer rate slightly between the injector and the liquid.

5.1.1 Issues with Injector One

The reason this injector had to be modified to work properly at the mass flow of 100 mg/s of water is that the heat transfer between the injector itself and the water was not adequate. The addition of the cap made the heat transfer somewhat higher but unfortunately not good enough for the same mass flow with the simulants. The addition of salt reduced the heat transfer enough so that no power could be
Chapter 5. Injector development

5.1. Injector One

![Injector One with Cap](image1)

![Injector One Cap](image2)

Figure 5.2: The improved Injector One

found where all the liquid was vaporized.

For water, the power needed to vaporize the whole mass flow was determined to 276 W with the injector cap. For less than 260 W, the injector got too cold and all of the water was not vaporized. For more than 280 W, the temperature of the injector got too high and the Leidenfrost effect occurred. The Leidenfrost effect occurs when a liquid comes in contact with a mass considerably hotter than the boiling point of the liquid. The part of the liquid in contact is instantly vaporized, forming a thin gas layer in between the hot mass and the liquid, isolating it and thus reducing the heat transfer significantly. In Figures 5.3 & 5.4 one can see how sensitive this injector is, keeping in mind that 276 W was the determined nominal power. This meant that the injector had a range of roughly 20 W where it worked. This range is dependent on the heat transfer between the injector and the liquid.

![Temperature during 280 W test](image3)

Figure 5.3: Temperature during 280 W test. Note how it seems to settle after approx. 350 minutes. TC1-6 is the temperature of the injector body

When a mixture of AA and water (40/60 mass percentage) was tested in the injector, the injector was either too cold, not vaporizing the mixture, or, for a slightly higher power, too hot - triggering the Leidenfrost effect and thus not vaporizing the mixture. This proved that the heat transfer was not in the range of the power needed to vaporize the mixture, thus the injector could not vaporize all of the flow.
Chapter 5. Injector development

5.1.2 Improvements to Injector One

The issues mentioned led to the investigation of how to improve the injector once again. One way of increasing the heat transfer between the liquid and the injector is to increase the contact surface. Thus, the seven small holes were partially filled with steel wires, which were thought to conduct heat from the inner walls to the liquid. The result was however negative. The heat transfer was reduced and the Leidenfrost effect occurred at much lower powers than without the wires. Two experiments were carried out, one with 12 pieces of 0.1 mm diameter wires in each 2 mm diameter hole, and one with 24 of the same wires in each hole. The latter one performing even worse. Figure 5.5 shows how the 12 and 24 wires are placed in each hole.

One reason to why the wires failed might be that the contact between the wires and the injector itself is small, thus the wires did not conduct much heat at all. Since the wires partially filled the holes, the velocity of the liquid increased, giving it a shorter time spent in the injector.

Another attempt was made with steel wool. Thin straws of steel wool were made as inserts for each hole. The straws of steel wool weighed about 0.6 g each and were fitted in the injector using a piece of wire. However, the steel wool clogged the holes and no liquid could pass through. In an attempt to remove these straws, some broke and the part that clogged was stuck inside the injector. Due to the difficulty of...
removing these packed steel wool pieces, no more attempts were made with steel wool.

Another issue with the first injector was that gas formed upstream and pushed liquid downstream out of the injector at high velocities, thus preventing the vaporization of this liquid. The cap, which makes the water maze instead of flow straight through the injector, partially prevented this. No water exited the injector, but the pressure buildups were still there and a “coughing” sound could be heard from inside the vacuum chamber. A non-constant flow was assumed because of this “coughing”.

The temperature gradient of Injector One could also be considered a problem. Since the liquid flow enters from one direction, and is relatively cold close to room temperature, and the cartridge heater is placed pointing forward in the injector, there is a temperature gradient of about 50 K/cm at the middle of the injector, shown as in Figure 5.6. This contributes to insufficient heat transfer, because at one point the injector is not warm enough and in the next it is too hot, causing the Leidenfrost effect.

Apart from this, Injector One weighed roughly 350 g because it’s massive stainless steel body. This also implies a high thermal inertia.

These issues, but more importantly, the fact that Injector One could not completely vaporize the simulants for the nominal value of 100 mg/s, meant that a new injector had to be designed.

5.2 Investigated concepts

When the decision was taken to design a new injector instead of trying to further improve Injector One once more, different designs are investigated in order to see practical advantages and disadvantages. Six main attributes/criteria are thought of when the concepts were developed:

- Sufficient heat transfer
- Low thermal losses
- Low thermal inertia
- Low weight
- Chemically resistant
- Temperature tolerant

In this chapter, four concepts are presented.

5.2.1 Heating pipe

The heating pipe concept shown in Figure 5.7 is based on using the pipe itself as the heat source. This is done by applying a current to a stainless steel pipe using the resistance in the pipe. The pipe, which
has to be long to reach a desirable resistance, is then wound into a spiral shape for a more compact design.

![Heating Pipe concept - Front view](image1) ![Heating Pipe concept - Rear view](image2)

Figure 5.7: Two views of the Heating Pipe concept

This single pipe has a Reynolds number of 270, compared to the Reynolds number for Injector One of 20. However, the increase in Reynolds number does not make much difference until the flow becomes turbulent at $Re=4000$, which is not the case. The smaller diameter of the pipe and the larger surface contact compared to Injector One gives it a higher convective heat transfer for equal temperature differences. The length of the pipe should also allow for a smaller gradient temperature than that of Injector One, which was 50 K/cm.

The losses will be low because of the lower temperatures in the pipe. Because of the low mass, weight will be low compared to Injector One and the initialization should be fast. Since the pipe is made of stainless steel, it will be rather chemically resistant and temperature tolerant. All six criteria are fulfilled.

### 5.2.2 Wound Pipe

The Wound Pipe concept, Figure 5.8, is similar to that of the Heating Pipe, but instead of leading a current through it the pipe is wound on a resistive heating element. If a cartridge heater is embedded in an aluminium cylinder with a radius of 20 mm and a length of 80 mm, roughly 2.7 m of pipe can be wound on it. The length of the pipe is similar to that of the heating pipe and thus, the heat transfer should be close to equal for the same temperature difference.

![The Wound Pipe](image3)

Figure 5.8: The Wound Pipe

This design should have sufficient heat transfer for a long enough pipe. It will also be light weight giving it a low thermal inertia and low losses. A stainless steel pipe could be used, making the Wound Pipe concept chemically inert.
5.2.3 Porous Stick

The porous stick concept, Figure 5.9, is based on a bismuth vaporizer developed at NASA [24]. The idea is that the liquid will flow through a porous graphite stick. The graphite stick then carries a current and is heated due to the electrical resistance in the graphite material. The plug is enclosed in a ceramic tube and connected to electrodes at the ends.

![Porous Stick](image)

(a) The whole “stick”  
(b) The electrodes

Figure 5.9: Porous Stick injector

This way, the contact surface between the liquid and the solid material will be huge compared to in the Injector One. This should ensure a sufficient heat transfer. The injector will be very small in size, have a low weight and fast heating. Both glass and graphite are very chemically resistant and temperature tolerant, so this concept also fulfills all six criteria.

5.2.4 Porous Injector

The second porous stick idea is a simplified concept of the first porous plug concept. Instead of actively heating the porous material, a cartridge heater is enclosed in a thick cylinder of a porous ceramic which in turn is enclosed in a thin stainless steel cylinder shown in Figure 5.10. The cartridge heater then heats the porous material from the inside, vaporizing the liquid flow.

![Porous Injector](image)

Figure 5.10: The Porous injector

This Porous injector concept also fulfills all criteria.

5.3 Injector Two

The Heating Pipe concept was discarded due to the risk of creating a magnetic field around the injector. The Porous Stick concept was also discarded due to difficulties of finding a supplier for the porous material.

Since all the necessary equipment and materials to manufacture the Wound Pipe concept were available, it could be built. Though the Porous Injector was also considered for manufacturing, the Wound Pipe
was both cheaper and could be made quickly, without having to wait for materials to be delivered.

The wound pipe concept is built as follows: a 400 W cartridge heater of the same model as was used in Injector One is placed within a threaded aluminium core. A 2.6 m 1/16 in. stainless steel pipe is wound on the aluminium core. A stainless steel cylinder is placed enclosing the pipe, keeping it in place as well as forcing it against the aluminium core. This is to ensure maximum surface contact between the pipe and the core.

A sketch of Injector two is shown in Figure 5.11. Each component is shown in a unique color.

![Figure 5.11: A sketch of Injector Two. The cartridge heater (red) placed in the aluminium core (grey) which the pipe (blue) is wound on. The outer casing (yellow) keeps everything in place.](image)

In Figure 5.12, the manufactured Injector Two is shown on its mounting. The small attachments are used to attach the thermocouples.

![Figure 5.12: Injector Two](image)

### 5.3.1 Thermal analysis

A thermal analysis of the injector and the injector plume is needed in order to determine the heat transfer from the hot injector and the gas to the EIMPAC'T. The permanent magnets of the EIMPAC'T are very sensitive to higher temperatures: they begin to permanently lose their efficiency if they reach temperatures of 200°C or more. In order to design the thruster so that the thermal flux from the injector to these magnets need to be low enough to keep the temperature lower than 80°C, the temperature of the injector and the plume is studied.

Thermocouples are attached to the injector to measure its temperature. To study the thermal flux from the injector plume to the thruster chamber a quartz tube with the same dimensions as in the thruster is used. This quartz tube is also equipped with thermocouples.

In order to know how the injector behaves for different powers and how the plume temperature depends on the applied power, a series of tests were planned for each mixture. All the considered tests are presented in Table 5.1.
Chapter 5. Injector development 5.3. Injector Two

<table>
<thead>
<tr>
<th>100% Flow</th>
<th>90% Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{min}}$</td>
<td>$P_{\text{min}}$</td>
</tr>
<tr>
<td>H2O</td>
<td>1</td>
</tr>
<tr>
<td>Bi. Hi</td>
<td>1</td>
</tr>
<tr>
<td>Bi. Low</td>
<td>2</td>
</tr>
<tr>
<td>Full Hi</td>
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</tr>
<tr>
<td>Full Low</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>50% Flow</th>
<th>10% Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{min}}$</td>
<td>$P_{\text{min}}$</td>
</tr>
<tr>
<td>H2O</td>
<td>1</td>
</tr>
<tr>
<td>Bi. Hi</td>
<td>1</td>
</tr>
<tr>
<td>Bi. Low</td>
<td>2</td>
</tr>
<tr>
<td>Full Hi</td>
<td>1</td>
</tr>
<tr>
<td>Full Low</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.1: Test points with priorities from 1 (Highest) to 3 (Lowest). *Long run, 2h of temperature stability of injector body

First the minimum power ($P_{\text{min}}$) for complete vaporization is sought for each mixture and flow rate. This is either done by starting at a power lower than $P_{\text{min}}$, which is increased each time a thermal equilibrium is reached until a thermal equilibrium with complete vaporization is achieved, or by starting the flow with a preheated injector and at a power higher than $P_{\text{min}}$, decreasing the power in steps until droplets begin to exit the injector.

Having found $P_{\text{min}}$, an additional 5 W is added in order to see how much of these 5 W results in losses and how much it additionally heats the gas.

These $P_{\text{min}}$+5 W tests are repeated with an additional 10 W to the $P_{\text{min}}$, known as nominal power ($P_{\text{nom}}$), or 10%, for the 10 mg/s mass flow rate. $P_{\text{min}}$+50 W for a 100 mg/s mass flow rate and 2 $P_{\text{nom}}$ for 10 mg/s mass flow rate (called $P_{\text{max}}$) are also chosen to see what happens when using excessive power.

For H2O and the Full mixtures, “choke-tests” are run where the nominal power is used but the mass flow rate is choked in steps of 10% until the temperature of the injector body reaches 500-600°C. Exceeding these temperatures would damage the aluminium core of the injector which melts at about 660°C, and probably has a higher temperature than the measured temperature on the stainless steel casing.

5.3.2 Pressure analysis

Because the new injector design has thin pipe and the fact that LMP-103S has a higher viscosity than water, the pressure drop over the injector is investigated.

The viscosity of LMP-103S changes with temperature, see Figure 5.13, but for a worst case scenario corresponding to high viscosity, the viscosity at a temperature of 20°C is used through all of the pipe. When heating and vaporizing the LMP-103S, the pressure drop decreases.

The pressure drop can be expressed as

$$\Delta p = \frac{64 \ l \ \rho v^2}{R_d d^2}$$

where $l$ is the length of the pipe, $d$ the inner diameter, $\rho$ the density of the fluid, $v$ the velocity of the fluid and $R_d$ is Reynolds number.
Figure 5.13: Viscosity of LMP-103S and water

\[ R_e = \frac{\rho v d}{\mu} \]  \hspace{1cm} (5.2)

For the worst case scenario, with no heating of the LMP-103S, the pressure drop over the injector is calculated to 0.35 mbar for 100 mg/s, which is not a problem. However, an experimental test with 1-Hexanol, with viscosity close to equal that of LMP-103S at room temperature, is used to confirm if the calculations are wrong or not. The result from the experiment is shown in Chapter 7.5 Pressure Analysis.
Chapter 6

Test setup

6.1 Overview

The test is performed at OHB Sweden, in a vacuum chamber with the injector mounted inside, along with several systems such as: heater control, liquid feeding, a vacuum pump and its exhaust filters and several other smaller subsystems. A sketch of the test setup is shown in Figure 6.1. Both a pressure regulator (PT) and a vacuum gauge (VG) is used to monitor the pressure in the vacuum chamber. A cooling system is used to condense the gas onto a cold surface inside to decrease the pressure even further. Thermocouples are used to monitor the temperature of the injector as well as the quartz tube.

All essential systems are presented in this chapter.

Figure 6.1: An overview of the test setup

A sketch of how everything is connected is presented in Appendix B.

6.2 Vacuum Chamber

The vacuum chamber used for the HPEP experiments is of an older type and deemed expendable if damage occurs. The vacuum chamber allows the testing to be performed in a somewhat realistic environment, similar to that in which the final thruster is intended to work in. It has two lids, one in the front and one in the back. The front of the chamber is equipped with a view port which allows visual verification
of the experiment. The back of the chamber is the interface for all equipment inside. This interface is shown in Figure 6.2.

![Figure 6.2: The vacuum chamber interface with each feed-through marked for its purpose](image)

The vacuum chamber has the inner diameter of 0.51 m and a length of 0.8 m, and an inner volume of roughly 650 liters.

Inside the vacuum chamber, Figure 6.3, the injector is mounted on a strut, but is thermally isolated from it using a low conducting shim. Where the injector ends, the quartz tube begins. The tube is mounted so that the injector is aligned with the centerline of the tube.

![Figure 6.3: Overview inside the vacuum chamber](image)

The condenser is placed behind the injector and the quartz tube.
6.3 Heater Control

The cartridge heater is powered by a DC power supply, model TDK-Lambda, which can deliver up to 750 W. This power supply does not provide a constant power, but a constant voltage. The current is determined through the resistance which varies depending on the temperature. Therefore, the power supply is connected to a multimeter, measuring both voltage and current. The multimeter is in turn connected to a computer which controls the DC power supply with the aid of Labview, in order to deliver a constant power.

6.4 Liquid feed

The liquid mixtures are fed to the injector using a “high-performance liquid chromatography” (HPLC) pump. The reason this pump is used is that the flow needs to be steady and very accurate. Letting the vacuum in the chamber simply suck the liquid from the source would not allow for any kind of controlled flow.

The HPLC pump together with a needle valve allows for a controlled and very fine mass flow. Upstream of the needle valve is a protective filter. This filter is specified to block 95% of all particles of size 2 µm, or above.

To measure the mass flow and verify that the HPLC pump is providing the correct flow, a scale is used to measure the weight of the mixture reservoir. The weight of the reservoir is measured during several times during a test and the mass flow rate can be calculated.

6.5 The vacuum pump and exhaust filters

This is a system of three components. The first component is the vacuum pump, Figure 6.4a, which creates the vacuum in the vacuum chamber and also removes the fumes from the test environment. This vacuum pump is a Ilmvac MPC1801Z chemically resistant diaphragm vacuum pump with the ultimate pressure of 8 mbar.

The second component is a scrubber/acid trap, Figure 6.4b, with the single purpose of collecting the harmful waste of the mixtures. The scrubber seems to collect more vapor being placed downstream the vacuum pump rather than upstream. This setup is fine because of the fact that the diaphragm pump is chemically resistant.
Downstream the scrubber, the exhaust will pass through a second filter, Figure 6.4c, before it is let outside. This filter is an ABEK filter used in face-masks to filter organic vapors, inorganic gases (excluding carbon monoxide), acidic gases, ammonia and organic ammonia derivatives. The filter is connected to a hose, coming from the acid trap, using duct tape. Duct tape is also used to seal the flex tube around the filter. As can be seen in Figure 6.4c, downstream the filter is a flex tube connected to the wall, where the remaining gases are let outside.

### 6.6 Condenser

The condenser has the single purpose of decreasing the pressure even further by keeping the fumes at lower levels through condensation on the cold surface. It is cooled by a cooling system, Julabo FP50, circulating \( \sim 24 \) liters per minute and has a cooling power of 500 W at \(-20^\circ\text{C}\). It is however only used to cool the condenser to a temperature of \(-10^\circ\text{C}\), which is more than enough to condense a lot of the fumes.

### 6.7 Thermocouples

A total of 16 thermocouples, type K, are used to monitor the temperature of the injector and the quartz tube as well as the gas temperature, the wall temperature and the inlet temperature. The injector is equipped with seven of these thermocouples, Figure 6.5. The temperature measurement tells where in the injector the evaporation takes place by showing where the temperature increases significantly, indicating less heat transfer due to gas filling the pipe instead of liquid.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1-6</td>
<td>Injector Body</td>
</tr>
<tr>
<td>TC7</td>
<td>Injector Plume</td>
</tr>
<tr>
<td>TC8</td>
<td>Injector Inlet</td>
</tr>
<tr>
<td>TCB1-6</td>
<td>Quartz Tube</td>
</tr>
<tr>
<td>TCB7</td>
<td>Vacuum Chamber Wall</td>
</tr>
<tr>
<td>TCB8</td>
<td>Injector Tip</td>
</tr>
</tbody>
</table>

Table 6.1: Location of each thermocouple

The temperature of the quartz tube is also measured in order to know how much the plume, and the radiated heat from the injector, would heat the last stages of the engine. There are four thermocouples mounted in a row on the quartz tube, 10, 60, 140 and 200 mm away from the injector along the axis, Figure 6.6. Another two were mounted on the opposite side of the tube from the nearest and furthest thermocouple. Additionally, one thermocouple is placed inside the quartz tube to monitor the plume temperature (TC7).

![Figure 6.5: The thermocouples positions on the injector](image-url)
6.8 Issues

One issue with the test setup is that the HPLC pump stops delivering the flow rate it is supposed to deliver at some times. This is both measured using the scale but is most easily seen by looking at the temperature of the injector. When the flow rate decreases, the temperature of the injector rises very fast.

Several reasons to why the HPLC pump was malfunctioning were found: any one of the four check valves clogged occasionally, resulting in only half the flow rate, any of the three filters (mobile phase filter, outlet filter and needle valve filter) were clogged, and even the needle valve itself was sometimes clogged.

This was initially believed to be caused by the high concentration fluids but the fact that the cheap brands used for the Ammonium Acetate with only 97-98% salt is not pure, was probably the most contributing factor.

Each time a filter or a check valve clogged, the HPLC pump was disassembled and the check valves and filters were plunged in an ultrasonic bath for cleaning.

Apart from the clogging, the plunger seals were old and leaking, causing salt to enter the mechanical parts of the pump, creating huge friction and slowing the pump down. Because of this, it was serviced and lubricated from time to time.

The vacuum chamber started leaking through one of the several feed-throughs several times, causing a pressure increase inside the chamber. This issue was dealt with using silicone sealant.
Chapter 7

Results

7.1 Losses

In Chapter 4.5 *Losses*, the effective emissivity coefficient was measured to be roughly 0.5 and assumed not to change much with temperature for temperatures below 400°C. All the tests with water were used to make a model of how the convective heat loss depended on the mass flow rate through the injector.

The power needed to evaporate each mass flow rate together with the conductive losses and the radiative losses was compared to the applied power on the cartridge heater. This difference was assumed to be convective heat loss with no model errors at all.

The convective heat transfer coefficient was then solved for in equation 4.12. This coefficient is shown for each flow rate of water in Figure 7.1.

![Convective heat transfer coefficient, h, as function of mass flow](image)

Figure 7.1: Convective heat transfer coefficient, h, as function of mass flow

A linear approximation is made and used for calculating the convective heat transfer for each mass flow rate.
7.2 Power calculations

With a complete model for the power needed to vaporize a mixture for a certain flow, the calculations are made. These values are then used as an initial estimate for what the real minimum power for vaporization ($P_{\text{min}}$) is.

The tests can either be started with a lower power where a thermal steady state is found, and then increased in steps, waiting for steady state each time, until all of the liquid is vaporized and nothing can be seen exiting the injector. Alternatively, the injector is preheated so that there is full vaporization at the beginning of the test and the power is then lowered, in steps where each steady state is found, until droplets can be seen exiting the injector. Both methods have advantages: starting from a low temperature and increasing the power requires less time, however, starting at a high temperature and decreasing the power gives less salt condensation on the quartz tube and the injector.

One more way of seeing when $P_{\text{min}}$ is reached is by studying TC6’s temperature compared to the other thermocouples on the injector body. Once this temperature increases more than the others, it indicates that the point of complete vaporization is found at the part of the injector where TC6 is located. Because of the fact that there is only gas at this point, the cooling effect of the liquid is lost and thus the temperature increases. Increasing the power even more at this point, TC5 will display a larger temperature increase, showing that the point of vaporization is moved to an earlier part of the injector.

In Table 7.1, the experimentally determined minimum powers to vaporize the mixtures for different mass flow rates are compared to the theoretical values calculated including the losses.

<table>
<thead>
<tr>
<th>Flow [mg/s]</th>
<th>100</th>
<th>90</th>
<th>50</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O [W]</td>
<td>285/283</td>
<td>255/255</td>
<td>140/140</td>
<td>29/29</td>
</tr>
<tr>
<td>Binary (Hi) [W]</td>
<td>235/237</td>
<td>217/212</td>
<td>115/116</td>
<td>26/24</td>
</tr>
<tr>
<td>Binary (Low) [W]</td>
<td>240/242</td>
<td>220/216</td>
<td>117/118</td>
<td>27/24</td>
</tr>
<tr>
<td>Full (Hi) [W]</td>
<td>200/199</td>
<td>178/178</td>
<td>97/96</td>
<td>22/20</td>
</tr>
<tr>
<td>Full (Low) [W]</td>
<td>220/215</td>
<td>198/191</td>
<td>107/104</td>
<td>24/22</td>
</tr>
</tbody>
</table>

Table 7.1: Comparison between experimentally (in bold) and theoretically determined minimum power for complete vaporization

The search for the minimum power to vaporize ($P_{\text{min}}$) is done in steps of 5 W for the tests with 100 mg/s flow, 2 W steps for tests with flow of 90 & 50 mg/s and steps of 1 W for the tests with a flow of 10 mg/s.

During the tests with the simulants, it was shown that the Ammonium Acetate did not decompose as initially suspected, but instead vaporized and then condensed inside the quartz tube and on the vacuum chamber wall, as shown in Figure 7.2. The crystal structure of the salt condensing depended on the mixture itself, a comparison is shown with Figure 7.2a and 7.2b. For the Full mixtures, it was very clear that the Ammonium Acetate did not decompose, as it condensed all over the equipment.

This implies that the theoretical model is based on a untrue assumption. However, since the theoretical model was so accurate, the enthalpy of fusion and vaporization must be close to equal to the enthalpy of decomposition from a solid state. Thus, the enthalpy of decomposition from a gaseous state is negligible.
7.3 Injector vaporization potential

Injector Two shows that it can vaporize any of the required mass flows for any simulant to LMP-103S. It does this for low temperatures of the injector body and with a low temperature gradient, Figure 7.3.

The injector was put to the test with a mass flow of 165 mg/s of water, where it managed to evaporate all of the flow at a power of 450 W. Since the cartridge heater is specified for 400 W, no higher flows or powers were tried. Even though evaporating this mass flow of water cannot be compared to evaporating the same mass flow of LMP-103S since the heat transfer between the injector and the fluids are not equal, it still clearly shows that there is a margin for the nominal flow of 100 mg/s for LMP-103S.

7.4 Thermal analysis

A thermal analysis was made to investigate the thermal behavior of the injector. Both the injector temperature, the temperature of the quartz tube and the plume temperature were measured and compared with the power supplied during the test.

A typical temperature distribution during a $P_{nom}$ test can be seen in Figure 7.4.

The injector temperature, taken as the average of all six TCs, increase with power linearly for powers
7.4. Thermal analysis

giving temperatures below 300°C. However, for higher temperatures, the relation looks more like a logarithmic trendline, which is consistent with the fact that the radiative losses are a function of the absolute temperature to the power of four. Figure 7.5 shows how the temperature increases with power for each mass flow rate. The logarithmic trendline can be imagined in Figure 7.5d. A relation is drawn between the AA concentration and the temperature for $P_{\text{min}}$, the more AA the higher the temperature. This probably depends on the heat transfer being reduced, which was seen for Injector One as well.

![Figure 7.4: Temperature evolution during $P_{\text{nom}}$ test with 100 mg/s of Full-High mixture](image)

The plume analysis proved to be more complex. The temperature of the gas was measured by TC7, located approximately 30 mm away from the injector tip. These temperatures were compared with the powers on the injector, or rather the excess powers. In Figure 7.6 the temperatures are shown for the excess powers, meaning the additional power to $P_{\text{min}}$ for $\text{H}_2\text{O}$. A linear trend can be imagined but some of the data is showing inconsistencies.

Three out of four $P_{\text{min}}$ tests show a gas temperature between 26°C to 31°C which is the boiling point for $\text{H}_2\text{O}$ at these low pressures. When comparing the power needed to raise the temperature of the gas to the measured gas temperature and the actual excess power, an efficiency number could be calculated. However, these numbers proved very inconsistent, probably because of the fact that measuring gas temperature in low pressure environments is unreliable and the plume is probably cooled down by sucking...
This analysis could not be done for the full mixtures due to condensation on the TC7, see Section 7.6.1 \textit{Salt condensation}.

The temperature of the quartz tube was measured to see how much heat the injector plume would transfer, and the injector would radiate, to the rest of the engine. The $P_{\text{nom}}$ tests for 100 mg/s of flow rate was used to study the temperature evolution of the quartz tube. In Table 7.2 the average temperature of the quartz tube is shown for each mixture at the end of a $P_{\text{nom}}$ test.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Avg. Temperature [°C]</th>
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<tr>
<td>H$_2$O</td>
<td>28.3</td>
</tr>
<tr>
<td>Binary (Hi)</td>
<td>33.7</td>
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<td>Binary (Low)</td>
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<tr>
<td>Full (Hi)</td>
<td>41.0</td>
</tr>
<tr>
<td>Full (Low)</td>
<td>40.8</td>
</tr>
</tbody>
</table>

Table 7.2: Average temperature of quartz tube at end of $P_{\text{nom}}$, 100 mg/s test for each mixture

The typical temperature distribution of the quartz tube can be seen in Figure 7.7.

**7.5 Pressure analysis**

Eight different tests are executed during the experiment, each test is done twice. The HPLC pump is used to measure the pressure with output in integer numbers. Hence, only a readout of 0 or 1 bar is
First, the pressure drop up until the injector is measured simply by disconnecting the injector and letting the HPLC pump give a flow rate of 6 ml/min of water. The injector is then connected and the pressure is measured again. This is repeated but with 1-Hexanol, another simulant used instead of LMP-103S with close to equal viscosity.

All these tests are again repeated with a flow rate of 10 ml/min. The result of all tests are seen in Table 7.3

<table>
<thead>
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<th></th>
<th></th>
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<tbody>
<tr>
<td>6</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1-Hexanol</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>Water</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>1-Hexanol</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.3: Pressure drop tests with water and 1-Hexanol

Only for the 10 ml/min flow with 1-Hexanol did the HPLC pump give 1 bar of pressure. This experiment shows that no significant pressure drop is measured over the injector for a normal flow rate.

### 7.6 Important observations

A few important observations were made during all of the experiments, some of which are good to consider for future reference, but some more important, having direct implications on the experiments and possibly even to the project.

#### 7.6.1 Salt condensation

As previously shown, the Ammonium Acetate did not decompose but instead vaporized and then condensed on most surfaces. This proved to be a problem when the quartz tube was clogged or salt had condensed on the thermocouple inside the quartz tube and built a crystal structure all the way back to the injector tip, covering it in salt and making it impossible to visually confirm complete vaporization. Figure 7.8 shows examples of when the condensing salt caused early abortion of experiment.

![Outside view of clog](image1)
(a) Outside view of clog

![Inside view clog](image2)
(b) Inside view clog

![Crystals covering the tip](image3)
(c) Crystals covering the tip

Figure 7.8: Condensation causing issues

In Figure 7.8c the reason why TC7 was not used is quite obvious. This much condensation was reached within 20 minutes when trying to find $P_{min}$ for Full-High mixture.

This problem only occurred for temperatures of the injector around that of $P_{min}$ up until about 300°C. At this point, the gaseous salt did not condense on the inside of the quartz tube any longer, but instead removed the already condensed salt.


7.6.2 Corrosion

The Ammonium Acetate, or some of the bi-products from what was decomposed ate at the equipment. Since these products were carried in the vapor and condensed everywhere, all metals that are not corrosive resistant are corroding rapidly.

Despite the fact that part of the equipment has corroded, nothing has yet failed or malfunctioned.

Some of the most corroded parts of the equipment are the thermocouple connections. However, when they were opened to investigate the corrosive impact, it turned out that no essential part of the connections itself is affected. Figure 7.10 shows the opened thermocouple connection.

![Figure 7.9: A corroded TC connection](image)

(a) TC connection on the outside  
(b) TC connection on the inside

Other parts that were clearly affected by corrosion are the hose clamps on the condenser. The two clamps on the left in Figure 7.10a are made of stainless steel, while the two on the right in Figure 7.10b are not.

![Figure 7.10: Corrosion of non-stainless steel hose clamps](image)

(a) Stainless steel hose clamps  
(b) Ordinary hose clamps

7.6.3 Critical temperature

For the Full mixtures, there is a temperature or a power level of the injector that evaporates all of the ammonia, all of the methanol and most of the water but the salt is not vaporized. This temperature or power is slightly below $P_{\text{min}}$. Leaving the injector is a viscous substance of salt and a tiny fraction of water. This has lead to salt encasing the injector tip, directing the flow in another direction and in a worst case scenario even clogged the pipe for a low flow.
7.6.4 Leidenfrost effect

The Leidenfrost effect that easily occurred for Injector One was only triggered during two tests: $P_{\text{max}}$ for both Full mixtures and a flow rate of 10 mg/s. When the temperature reached above 250°C, droplets started exiting the injector. This could also be seen on TCB8 mounted on the injector tip: when the injector body temperature went beyond 250°C this thermocouple indicated a significant temperature drop. This is seen in Figure 7.11.

![Figure 7.11: Leidenfrost occurs during Full-Low 10 mg/s $P_{\text{max}}$ test](image)

However, this Leidenfrost effect did not occur during the choke tests where temperatures of above 500°C were reached for mass flows as low as 40 mg/s.
Chapter 8

Conclusion

The power needed to vaporize the simulant to LMP-103S proved to be close the calculated power based on the theoretical model, even though the theoretical model is based on the false assumption that the Ammonium Acetate would decompose. This proves that the enthalpy change from a gaseous ammonium acetate to the decomposed state is small.

The injector development lead to a new working vaporizer which fulfills all the requirements and should, according to both calculations and experimental work be able to vaporize the required mass flow of LMP-103S. Important observations were made when vaporizing Ammonium Acetate: the salt condensation on the equipment, the corrosive products, the critical temperature and the Leidenfrost effect. These issues led to ideas on how to avoid this if it would occur for vaporization of LMP-103S and even when firing the HPEP thruster. For instance, the injector could be run for an even higher power, were the gaseous salt is too warm to condensate inside the plasma chamber. Even the chamber itself could be heated to prevent condensation. The corrosion can be dealt with using proper materials. The critical temperature is avoided by using excess power for the injector and the Leidenfrost effect is avoided by not using too much power.

In the continuation of the HPEP project, the injector will be tested with LMP-103S. The plume could be studied to confirm the theoretical study, the injector has to be integrated with the EIMPAcT and finally the HPEP thruster could be tested in a thrust stand.

Furthermore the injector itself could be improved by thermally isolating it, thus decreasing the losses. The aluminium core should be completely enclosed in order to spare it from the corrosive LMP-103S. It could be geometrically optimized and, if it was equipped with permanent thermocouples, it could be controlled by a temperature feedback look instead of controlling the power, thus pre-heating would never be an issue of either going too high or too low in temperature.
Bibliography


# Appendix A

## Chemical data

<table>
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<tr>
<th>Molecular Formula</th>
<th>ADN</th>
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<th>CH₄O</th>
<th>NH₃</th>
<th>H₂O</th>
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<tbody>
<tr>
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<td>77.08</td>
<td>32.04</td>
<td>17.03</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>378</td>
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<td>338</td>
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<td>Boiling point at 35 mbar [K]</td>
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<td>107900</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<td>Heat capacity (l) [J·mol⁻¹·K⁻¹]</td>
<td>161.28</td>
<td>52.7</td>
<td>79.5</td>
<td>80.8</td>
<td>75.37</td>
</tr>
<tr>
<td>Heat capacity (g) [J·mol⁻¹·K⁻¹]</td>
<td>-</td>
<td>-</td>
<td>61.43</td>
<td>35.06</td>
<td>33.6</td>
</tr>
</tbody>
</table>

Table A.1: Chemical data

*(Assumed not to change with pressure)*

*(At normal pressure)*
Appendix B

Test setup Connections

![Diagram of test setup connections]

Figure B.1: The test setup connections