MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

**INPE-12329-NTC/369**

# THE DESIGN OF A COLD GAS THRUSTER USED TO CREATE A MICROGRAVITY ENVIRONMENT

Anita Le Mair
Paulo Giácomo Milani
José Nivaldo Hinckel

Completion of my internship for my study Aerospace Engineering, supervised by Dr. José Nivaldo Hinckel and Paulo Milani, March 2005

INPE
São José dos Campos
2005

# APPROVAL

A mandatory part of the fourth year curriculum for students of the TU Delft is an internship, worth 18 ECTS. This report shows that the internship of A.F. Le Mair has been completed successfully and the stated requirements have been fullfilled.

Approved by:

____________________________________ Paulo Milani

____________________________________ Dr. José Nivaldo Hinckel

Date signed: 1 april 2005

# PREFACE

This project has been very special to me. For me it was an opportunity to work with different people and to learn about a different culture. The three months that I have stayed at INPE gave me a lot of insight in the Brazilian culture and language. I will never forget the moments sitting outside in the sun, drinking  a cup of coffee, enjoying the beautiful views of the gardins of INPE.

Ofcoarse I could not have done the project by myself and therefore I would like to thank a number of persons. First of all, I would like to thank my supervisors dr. Nivaldo Hinckel and Paulo Milani for making it possible to do my internship here at INPE. Then I would like to thank Suely Silva for helping me understanding C++ in a very short period of time and Paulo de Souza for suplying the support needed. Finally I would like to thank Neusa, Marcelo and Marcele, my Brazilian family, for letting me stay with them.

## SUMMARY

The availability of ground based microgravity test facilities is essential for the orderly development of equipment intended for use in a weightless environment. A goal of the Brazilian government is to obtain independence in space research and one way to reach independence is by developing such a ground based microgravity test facility. INPE, Instituto Nacional de Pesquisas Espaciais is developing a microgravity platform due to the advantages of low cost and a short turn-around time. A goal of this internship is to make a first design for a cold gas propulsion system that ensures a microgravity environment during the flight. It is only a first design, since the development of the microgravity platform is still in an early stage as well. A secondary goal of this project is to obtain more experience in the field of testing a cold gas propulsion system because the institute has never tested this kind of thruster before. The main conclusion that can be drawn from observations during the design process is that a maximum thrust of 100 N is large when using a cold gas system. It resulted in a more complex system, which led to various problems and a reduced performance. Therefore, for future missions it is recommended to use a smaller thruster. An important conclusion that can be made from observations during the testing is that a large improvement in performance can be made when the pressure inside the storage tank of Nitrogen is regulated. For this design, a blow-down system has been used, leading to a reduction of 30% in maximum thrust-level. This reduction can be avoided by providing a constant mass flow and thus a constant storage tank pressure. In spite of all the assumptions that have been made, the results turned out to be very consistent with the theoretical results. The tests gave a lot of insight in the processes that occur and it even validated some assumptions and speculations. Although still many improvements can be made, this project turned out to be successful.

# TABLE OF CONTENTS

# LIST OF SYMBOLS

| Symbol | Dimension | Meaning |
|---|---|---|
| $A$ | $m^2$ | Area of the tube |
| $A_e$ | $m^2$ | Exit area of the thruster |
| $A_t$ | $m^2$ | Throat area of the thruster |
| $a$ | $m/s^2$ | Acceleration of the platform |
| $a_{rel}$ | $m/s^2$ | Relative acceleration inside the platform |
| $c_D$ | - | Drag coefficient |
| $c_F$ | - | Thrust coefficient |
| $c_{Fopt}$ | - | Optimal thrust coefficient |
| $c_{Fvac}$ | - | Vaccuum thrust coefficient |
| $c^*$ | m/s | Characteristic velocity |
| D | N | Drag |
| dt | S | Time increment |
| e | M | Surface roughness |
| f | - | Friction factor |
| $f_T$ | - | Friction factor for full turbulent flow |
| g | $m/s^2$ | Gravitational acceleration |
| h | M | Height |
| $h_b$ | Km | Starting height |
| $h_e$ | Km | End height |
| $I_{sp}$ | S | Specific impulse |
| L | M | Length of tube |
| $L_{eq}$ | 1/m | Equivalent length |
| M | Kg | Total mass of Nitrogen |
| m | Kg | Mass of the platform |
| m | kg/s | Mass flow |
| $m_{in}$ | kg/s | Mass flow in |
| $m_{out}$ | kg/s | Mass flow out |

| | | |
|---|---|---|
| $p_a$ | $N/m^2$ | Atmospheric pressure |
| $p_c$ | $N/m^2$ | Combustion chamber pressure |
| $p_e$ | $N/m^2$ | Exit pressure |
| $p_0$ | $N/m^2$ | Pressure at sea level |
| R | $m^2/s^2*K$ | Gas constant |
| $Re_D$ | - | Reynolds number |
| S | $m^2$ | Cross-sectional surface of the platform |
| T | N | Thrust |
| $T_c$ | K | Temperature of the combustion chamber |
| $T_{max}$ | N | Maximal thrust |
| V | m/s | Velocity of the platform |
| Vc | $m^3$ | Volume of the combustion chamber |
| | | |
| $\Gamma$ | - | Vanderkerhoven function |
| $\gamma$ | - | Ratio of specific heats |
| $\mu$ | Pa | Viscosity |
| $\rho$ | $kg/m^3$ | Density |
| $\rho_0$ | $kg/m^3$ | Density at sea level |

# CHAPTER 1

# INTRODUCTION

The availability of ground based microgravity test facilities is essential for the orderly development of equipment intended for use in a weightless environment. A number of facilities have been developed to meet this demand and include drop tubes, drop towers, experimental aircraft, balloon drop capsules and sounding rockets. Each of these facilities have unique characteristics which make them suitable for different phases of development of a particular experiment.

A goal of the Brazilian government is to obtain independence in space research and one way to reach independence is by developing such a ground based microgravity test facility. INPE, Instituto Nacional de Pesquisas Espaciais is developing a microgravity platform due to the advantages of low cost and a short turn-around time. Another reason for choosing this option is that already a lot of knowledge about balloon drop capsules was available. Some years ago one microgravity platform was developed and operated successfully [1] and this time a larger platform is planned to be developed.

A goal of this internship is to make a first design for a cold gas propulsion system that ensures a microgravity environment during the flight. It is only a first design, since the development of the microgravity platform is still in an early stage as well. A secondary goal of this project is to obtain more experience in the field of testing a cold gas propulsion system.

The mission contains the following phases: first the microgravity platform will be taken to an altitude of 42 km using a balloon filled with helium or hydrogen. Afterwards the platform will be released and the drop velocity will increase rapidly; the platform will even obtain a supersonic velocity. The final phase will be the recovery phase and starts at a height of 20 km, where the velocity is decreased again by using a parachute. This in order to ensure a good landing and the possibility for re-use.

A first simulation has been made of the platform [2] and it concluded that the platform will operate between an altitude of 42 km to 20 km, giving sufficient time to slow down afterwards. This creates a total operation time of ± 50 sec during which microgravity is present. Other features will be very similar to a microgravity platform that has been developed by OHB-System [3]. Therefore already a good estimate of the mass of the platform can be given, which will be around 443 kg. This, together with the desired operation time leads to a requirement for the maximum amount of thrust of 100 N.

In order to create microgravity, the sum of the forces acting on the platform must be zero, meaning that the thrust should be equal to the drag. This results in a free fall of the platform. Only when it is in free fall, microgravity is obtained inside the platform because then its acceleration is equal to the gravitational acceleration and so the relative acceleration inside the platform is zero.

The density of the atmosphere increases exponentially during the flight and so does the drag. This means that a propulsion system is needed to provide the platform with an increasing amount of thrust. In order to provide the platform with this thrust during the flight, a valve is added that controls the gas feed into the combustion chamber and this valve is pulsed. The thruster then varies according to the pressure in the combustion chamber. In other words, during the flight, the opening time of the valve keeps increasing until the end when it is fully opened.

The selection of the type of propulsion has already been made, based on the simulation that was performed. Usually it is used for attitude control purposes since the best efficiency[1] of this system is obtained when only small amounts of $\Delta V$ are needed and this is not the case for this microgravity platform. However, this kind of propulsion system has been chosen for different reasons: other advantages such as being a simple and safe system and relatively cheap type of propulsion, led to the decision of using a cold gas system. Nitrogen

[1] By efficiency it is meant that the mass of the propulsion system is small compared to the entire mass of the spacecraft, while it provides sufficient thrust [4]

has been chosen as the propellant because it is also cheap, readily available safe and it does not contaminate the microgravity experiments.

In this report, the results of the design of the propulsion system are given. Also some tests were performed and the outcomes of these results will be provided as well. This is done in the following way: in Chapter 2 the outcomes of the design of the thruster will be given when only maximum thrust is considered. After, in Chapter 3, the pulsation of the thruster is determined that includes a simulation of the thruster. Then, in Chapter 4 the outcomes of the tests will be given. Finally, in Chapter 5, a comparison will be made between the simulation and the actual test outcomes and some conclusions will be drawn.

# CHAPTER 2

# DESIGN OF THE THRUSTER AT MAXIMUM THRUST

Reliability of the propulsion system is very important since it determines the quality of the amount of microgravity that is created in the platform. In this context, with reliability it is meant that the system should operate as predicted and should remain functional during the flight. A simple system is usually a reliable system and good predictions can be made about its functioning. Fewer processes occur when the system is operating so a better analysis can be made about the functioning of the system and it also means that fewer errors can occur.

The design of the thruster is based on the situation when it is operating at maximum thrust because at the end of the flight when the thruster is fully operating, it should deliver maximum thrust. In the first paragraph a brief overview will be given of the simulation that has already been made for this mission and it will discuss the level of maximum thrust. In the second paragraph the preliminary design of the thruster will be explained based on the conditions of maximum thrust.

## 2.1 Maximum thrust determined by earlier simulations

The simulation that has been made at this institute for this microgravity platform is based on a study performed by OHB-System in Germany [3] and for the geometric design of this platform some features are copied. This includes that the mass of the platform will approach the mass of the earlier study, as well as the cross-sectional surface, meaning that the mass is taken to be 443 kg and the cross-sectional surface 0.159 $m^2$. When the variation of density with height and the variation of drag coefficient with Mach number are included in the simulation, the same results were found as given by the German study.

The simulation that was already performed for this platform showed that after 48 sec the drag of the platform would be around 100 N when no thrust is applied. Since the performance of a cold gas thruster degrades at higher levels of thrust due to the rapid increasing total amount of propellant gas at higher levels of thrust, a maximum thrust level should be taken as small as possible. However, the amount of time that microgravity is maintained in the platform has to be maximised. Taking into account these two contradictory requirements 48 seconds of microgravity was found to be a reasonable amount of time in order to perform some experiments while the amount of maximum thrust was found to be reasonable in first instance. If, however, dimensions of the thruster come out to be unacceptable, some reconsiderations have to be made.

These decisions result in the following:

(1) $T_{max} = 100$ N

(2) $h_b = 42$ km

(3) $h_e = 32$ km

## 2.2 Design of the thruster at maximum thrust

First of all, the three main assumptions that have been made are listed below:

(1) The gas behaves as an ideal gas. For Nitrogen, this is allowed because compressibility effects start at higher pressures than considered in this context.

(2) The gas expands isentropically.

(3) No viscous effects have been taken into account, meaning that boundary layer effects have been disregarded and so any possible consequences of flow separation leading to shockwaves. However, the Summerfield Criterion states that when the exit pressure over the atmospheric pressure is larger than 0.35, the flow will remain attached. The design of the thruster has been made such that this criterion will always be fulfilled.

In order to calculate the dimensions of the thruster, the aerodynamic performance of the platform has to be taken into account. The design has to be such that shockwaves are prevented from entering the nozzle. By designing the nozzle in such a way that the flow is under expanded (the exit pressure is higher than the ambient pressure) at the exit of the nozzle at all times during the flight, no back flow can occur and no shockwaves can enter the nozzle. By designing the nozzle in such a way that the exit pressure equals the largest ambient pressure found during the flight, which is the ambient pressure at 32 km, it is guaranteed that the flow is under expanded during the entire flight. So the exit pressure can be found from the following expression when h = 32 km:

$$p_e = p_a = p_0 e^{-\frac{\rho_0 g h}{p_0}} = 2.1384 * 10^3 \, {}^{N}\!/_{m^2} \tag{2.1}$$

The properties of Nitrogen are obtained from [5] and are the following:

γ = 1,42
M = 28,0134 kg/mol
R = 296 $m^2/Ks^2$ and

$$\Gamma = \sqrt{\gamma}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}} = 0.06881 \tag{2.2}$$

Varying the pressure and temperature in the chamber affect the other parameters of the thruster. For the chamber temperature a value of 293 K has been chosen, while various values for the pressure have been used to see how it affects the other parameters. The pressures for which the rest of the parameters have been calculated lie between 10 and 20 bar. It should be noted that the chamber pressure only directly affects the throat and the exit diameter of the nozzle, so the dimensions of the thruster itself. It indirectly affects the mass flow, the characteristic velocity and the thrust coefficient because pressure has an effect on temperature when an ideal gas is considered. A choice was made for the chamber pressure after the results were considered.

[6] gives the values for the thrust coefficient, both the optimal thrust coefficient and the vacuum thrust coefficient for various values of the pressure ratio. Since both $p_e$ and $p_c$ are known, the value for the thrust coefficient could be determined. The pressure inside the combustion chamber has been varied and so the value of the thrust coefficient was varied as well. This been done in first instance by fitting a linear curve through the data for the thrust coefficient, which is a very rough estimate. This introduces errors but they will be corrected

afterwards. When a value for the chamber pressure has been chosen, the accurate value will be used in further calculations.

Now the characteristic properties of the thruster can be determined. This includes the characteristic velocity and the mass flow [7]:

$$c^* = \frac{1}{\gamma}\sqrt{RT_c} \tag{2.3}$$

$$m = \frac{T_{\max}}{c^* c_{Fvac}} \tag{2.4}$$

$$I_{sp} = \frac{T_{\max} g}{m} \tag{2.5}$$

For a given pressure ratio ($p_e/p_c$), a certain value for the thrust coefficient can be found from [6]. Also linked to this pressure ratio and this thrust coefficient, an expansion ratio can be found. The pressure ratio at maximum thrust is 0.0011 and the corresponding expansion ratio is 36.63. Using this, the actual dimensions of the thruster can be calculated by [7]:

$$A_t = \frac{T_{\max}}{c_{Fvac} p_c} \tag{2.6}$$

$$A_e = 36.63 A_t \tag{2.7}$$

The results of the calculations that have been made for various chamber pressures are shown in Table 2.1:

TABLE 2.1 - Outcomes for different values of the chamber pressure.

| $p_c$ (Pa) | m (kg/s) | $d_t$ (m) | $d_e$ (m) |
|---|---|---|---|
| **1,00E+07** | 0.1418 | 0.0088 | 0.0528 |
| **1,10E+07** | 0.1418 | 0.0084 | 0.0503 |
| **1,20E+07** | 0.1418 | 0.0080 | 0.0482 |
| **1,30E+07** | 0.1417 | 0.0077 | 0.0463 |
| **1,40E+07** | 0.1417 | 0.0074 | 0.0446 |
| **1,50E+07** | 0.1417 | 0.0072 | 0.0431 |
| **1,60E+07** | 0.1417 | 0.0070 | 0.0417 |
| **1,70E+07** | 0.1417 | 0.0067 | 0.0405 |
| **1,80E+07** | 0.1416 | 0.0066 | 0.0393 |
| **1,90E+07** | 0.1416 | 0.0064 | 0.0383 |
| **2,00E+07** | 0.1416 | 0.0062 | 0.0373 |

It is shown that not a lot of variation occurs when different chamber pressures are considered. A reason might be that the effect of pressure on temperature is not taken into account. In reality, when the pressure increases, the temperature increases as well resulting in a more energetic flow, which would lead to a decrease in the amount of gas used. Also, the dry mass of the system reduces as the pressure in increased. Therefore, a pressure of 20 bar has been chosen for the chamber pressure.

Corresponding to a chamber pressure of 20 bar, the values for the thrust coefficients are [6]:

$C_{Fopt} = 1, 677$

$C_{Fvac} = 1, 717$

For this thruster, the vacuum thrust coefficient has been used to determine the other parameters since the atmospheric density at the operating altitude will be low. Also, the thruster will never operate optimally and therefore the optimal thrust coefficient is not considered to be a good estimate.

This finally gives the following dimensions for the thruster:

**m = 0.1359 kg/s**

**$c^*$ = 428.57 m/s**

**$I_{sp}$ = 75 s**

**$A_t$ = 2. 912 * $10^{-5}$ $m^2$ => $d_t$ = 0.0061 m**

**$A_e$ = 0.0011 $m^2$ => $d_e$ = 0.0369 m**

## 2.3 Manufacturing the thruster

The design of the thruster has been completed by a drawing, which can be found in appendix A. During manufacturing an error occurred which led to an exit diameter of 35.5 mm, so the actual thruster is a bit different.

In order to finalise the design, some practical consideration had to be made. Since only little budget was available, it was decided that the combustion chamber would be made of an already existing pipe, made of aluminium. The diameter of the pipe was chosen to be as large as possible in order to reduce the length as much as possible. The thickness of the chosen pipe was 3.2 mm, which is thick enough to handle the pressure inside the chamber.

The thruster itself had to be connected to the combustion chamber. This is done by welding flanges to the pipe that are connected to the thruster itself through a thread, which is sealed using an o-ring.

In order to reduce the material that is used to manufacture the thruster, the diameter at the side of the connection was taken to be close to the exit diameter of the thruster. This is allowed, as long as the diameter of the entrance of the thruster is twice as large as the diameter of the throat. This ensures that the starting velocity of the gas inside the combustion chamber can be neglected and that Mach 1 is reached in the throat.

The thruster itself has also been made from aluminium because it is easier to manufacture and it is cheaper. This led to a total dry mass of the system of 2.86 kg.

# CHAPTER 3

# SIMULATION IN TIME

The performance of the thruster depends on how long the thruster can create a microgravity environment, with an acceleration inside the platform as constant as possible, using as little gas as possible. When it is able to create a microgravity environment for a longer period of time using the same amount of Nitrogen, the performance will be better. However, the most critical requirement is that the thruster provides an environment where the acceleration in the platform is as small and constant as possible. The simulation that has been made will determine the performance of the thruster.

As explained in the introduction, the thrust increases in time and therefore the thruster is operated in a pulsed mode. It has been simulated how the thruster will operate as a function of time. However, the functioning of the thruster is dependent on the volume of the combustion chamber[2] and this will be explained in the first paragraph. In the second paragraph the build-up of the program will be discussed together and finally the outcomes will be given.

## a) Dependence on the volume of the combustion chamber

The objective is to find the level of thrust at each moment in time that approaches drag as close as possible, this in order to maintain a microgravity environment. However, it is not possible to provide for a level of thrust exactly equal to the drag at each moment in time because there is a limitation on the opening time of the valve that ensures pulsed thrust. Therefore a certain upper and lower limit for the relative acceleration (this is the acceleration relative to the gravitational acceleration) has been chosen and the provided thrust should ensure that these boundary conditions are fulfilled.

[2] The term combustion chamber has been used although no combustion takes place. This is only done to clarify the descriptions.

The thruster can either react faster or slower and the reaction time is dependent on the volume of the combustion chamber. The larger the combustion chamber, the smaller is the pressure gradient, meaning a smaller pressure build-up, resulting in a larger reaction time. And so, a smaller combustion chamber, a faster reacting time. Depending on how fast the drag increases, one needs a smaller or larger pressure build-up. During the flight the drag increases exponentially, so in the beginning it only increases slowly. Then a small pressure build-up is preferred giving a more continuous amount of thrust, which approaches the drag better. However, later during the flight the drag increases rapidly and the pressure build-up should be fast as well, creating a fast build-up of thrust, otherwise the drag out runs the thrust. An optimum has to be found and one should keep in mind that the limiting factor is the minimum opening time of the valve.

It should be noted that it is possible that the thruster reacts too fast or too slow. When the thruster reacts too fast, and so the pressure build-up is too large, the thruster will not be able to create a relative acceleration that stays within the stated boundaries. If the thruster reacts too slow, the amount of drag will out run the thrust and the thruster will not be able to maintain a microgravity environment for the desired duration.

**b) Explanation of the simulation**

A number of assumptions have been made in order to simplify the calculations. For clarity, they are given in first instance:

(1) The pressure inside the storage tank is so large that it will not decrease during the operation. This means the gas enters the combustion chamber with a constant pressure, velocity and temperature. However, in reality, since it is a blow-down system this will not be the case and the temperature of the gas will decrease, both in the tank and the combustion chamber.

(2) The velocity inside the combustion chamber is nearly zero so the dynamic pressure that the gas has when entering the combustion chamber will be transformed to static pressure. This assumption is valid when the volume of the combustion chamber and the pressure inside the storage tank are large enough.

(3) It has been assumed that in the combustion chamber, a constant temperature is found, and it was given a value of 293.15 K.
(4) A constant speed of sound has been used, namely 340m/s.
(5) The atmospheric pressure and density are only dependent on the height .

The most important condition in this simulation is the condition for the relative acceleration ensuring the required level of microgravity in the platform, which can be derived from Newton's second law:

$$F = ma \tag{3.1}$$

and so:

$$a = \frac{T - D}{m} \tag{3.2}$$

finally:

$$a_{rel} = a - g \tag{3.3}$$

From this requirement of a certain maximum amount of relative acceleration, the amount of thrust was calculated and for this simulation $a_{rel}$ = 0. 001*g was chosen, meaning a threshold of 0.001. There is an upper and lower boundary, namely ± 0.001*g (the sign indicating the direction) and both occur at different moments in time. A description of the physical phenomenon is given below in order to clarify the requirements in abstract form.

The drag increases and at a certain moment in time, the lower boundary is reached. The valve opens and the pressure inside the combustion chamber increases. This results in thrust and the relative acceleration decreases. However, when the thruster remains operating, the upper boundary will be reached and the valve will close again. Then the pressure in the combustion chamber will decrease since the atmospheric pressure is lower than the pressure in the chamber and gas will continue to flow out. At a certain moment, the lower boundary is reached again and the circle is complete.

This means that feedback can be given by using the pressure increase or decrease or through the relative acceleration. The feedback that controls the valve results in a fixed amount of mass flow into the combustion chamber since the valve cannot be partially opened. This means that when the valve is opened, the mass flow into the combustion chamber will be the maximum mass flow in order to be able to operate at maximum thrust. When translating this into conditions that have to be satisfied, the following is obtained:

If $a_{rel}$ < threshold * g and dp/dt > 0
  $m_{in} = m_{max}$
Elseif $a_{rel}$ >= threshold * g and dp/dt > 0
  $m_{in} = 0$
Elseif $a_{rel}$ > threshold * g and dp/dt < 0
  $m_{in} = 0$
Elseif $a_{rel}$ <= threshold * g and dp/dt <= 0
  $m_{in} = m_{max}$
Else $m_{in} = 0$
End

Now in order to know the relative acceleration of the platform, the forces that act on the platform need to be known at each moment in time. Because the thrust is dependent on the drag, the drag is calculated in first instance. The drag can be calculated with:

$$D = 0.5 \rho V^2 c_D S \tag{3.4}$$

and it is dependent on the altitude and the Mach number of the platform.

A time interval of 0.1 seconds has been used for the discretisation period in the simulation and during this time interval, the following calculations have been made after which the loop is completed. For each step, so for each 0.1 s, the velocity is calculated from the acceleration of the platform and the height from the velocity, using a linear Euler integration method. In order to calculate the density, a formula based on the standard atmosphere has been used that is only dependent on height [8]. The drag coefficient is heavily dependent on the Mach number and it increases rapidly as Mach goes to one. The relation however, is nonlinear and in order to find the drag coefficient without very complicated computations, three broad regions have been identified, namely:

If M < 0, 8
    $c_D$ = 0, 25
Elseif M > 0, 8 or M < 1, 5
    $c_D$ = 0, 4
Elseif M > 1, 5
    $c_D$ = 0, 35
End

Since the drag is known and using the conditions for relative acceleration, the valve is either opened or closed, giving a mass flow in or not. When mass flows in, there is a pressure gradient inside the combustion chamber

The equation of the pressure gradient is a differential equation, which has been found by differentiating the state equation with respect to time:

$$p = \rho R T_c = \frac{m}{V_c} R T_c \tag{3.5}$$

Taking the derivative while keeping the temperature constant, gives:

$$\frac{dp}{dt} = \frac{RT_c}{V_c}\frac{dm}{dt} = \frac{RT_c}{V_c}(m_{in} - m_{out}) \tag{3.6}$$

Using a linear Euler integration method, the new pressure inside the chamber is found. Now the new thrust can be found, using the new pressure. The thrust is calculated using [7]:

$$T = p_c c_F A_t \tag{3.7}$$

For this calculation, the thrust coefficient has been used. This coefficient changes with chamber pressure, exit pressure and atmospheric pressure. The thrust coefficient is calculated with [7]:

$$C_F = \Gamma \sqrt{\frac{2\gamma}{\gamma - 1}\left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} + \left(\frac{p_e}{p_c} - \frac{p_a}{p_c}\right)\frac{A_e}{A_t} \tag{3.8}$$

The atmospheric pressure used in this equation has to been obtained through:

$$p_a = p_0 e^{\frac{-\rho_0 g h}{p_0}} \tag{3.9}$$

The exit pressure used in the expression for the thrust coefficient is dependent on the chamber pressure and has been found using [7]:

$$\frac{A_e}{A_t} = \frac{\Gamma}{\sqrt{\frac{2\gamma}{\gamma - 1}\left(\frac{p_e}{p_c}\right)^{\frac{2}{\gamma}}\left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}} \tag{3.10}$$

Rearranging gives:

$$p_e = \left(\frac{\Gamma^2}{\left(\frac{A_e}{A_t}\right)^2 \frac{2\gamma}{\gamma - 1}}\right)^{\frac{\gamma}{2}} p_c \tag{3.11}$$

Finally the loop is closed by calculating:

(1) The new mass flow out of the combustion chamber

(2) The new acceleration of the platform

And by updating the following parameters:

(1) The pressure gradient

(2) The chamber pressure

(3) The acceleration of the platform

(4) The velocity of the platform

(5) The height of the platform

The program that has been used can be found in Appendix B.

It must be noted that the period of time that the valve is kept open or closed is not fixed, but increases as the flight progresses. This problem can be circumvented by taking the time step, for which all the calculations are made, sufficiently small. By adding up the number of cycles that it is opened, the total opening time can be found. Anyway, by decreasing the time interval, the operation of the thruster is improved. However, there is a limitation on the opening time of the valve and a minimum opening time of 0.1 s has been considered. Therefore the simulation has been made for a time increment of 0.1 s.

**a) Results of the simulation**

At the beginning of the chapter it has been said that the performance of the thruster depends on how long the thruster can create a microgravity environment, with an acceleration inside the platform as constant as possible, using as little gas as possible. The smallest size of combustion chamber for which the relative acceleration stayed within the stated boundary conditions for a longest period of time was $V_c = 0.005\ m^2$. When a larger combustion chamber was used, the duration for which a microgravity environment was created became shorter, while for a smaller size of combustion chamber, the quality of microgravity would degrade. The difference between the obtained relative acceleration for two sizes of combustion chamber is shown in Figure 3.1.

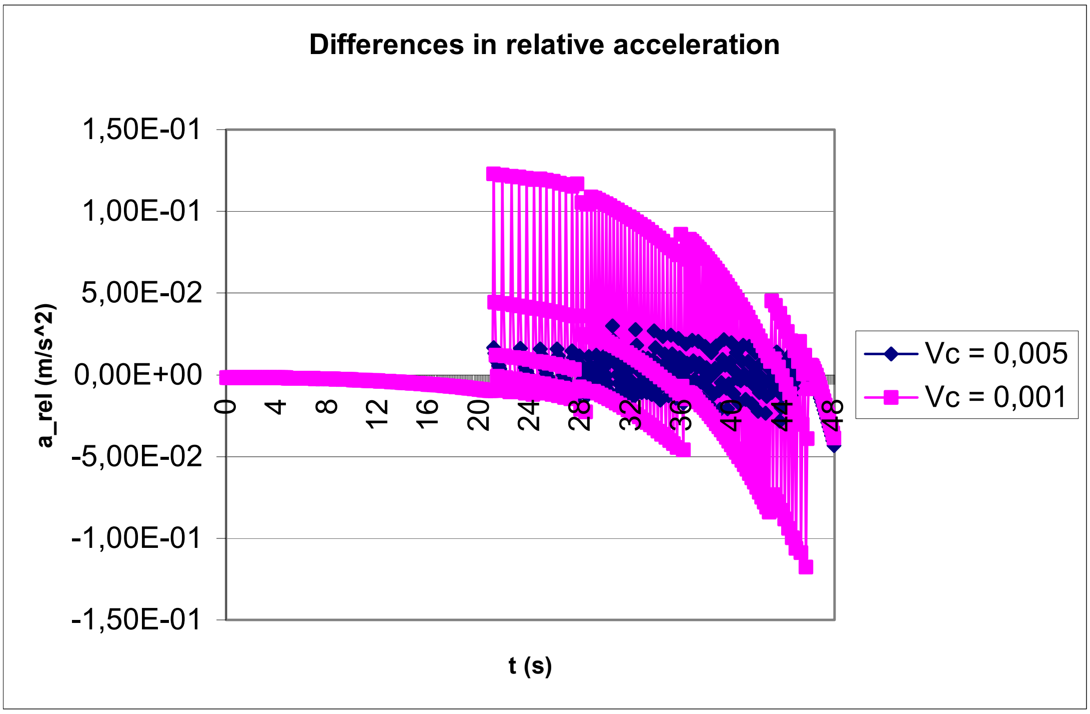



FIGURE 3.1 – Effect of chamber volume on the relative acceleration.

If, however, the minimum opening time could be reduced, the performance of the thruster using a smaller combustion chamber would improve since the thruster would have a smaller amount of time to build-up pressure  in the combustion chamber.

In general, the smaller the combustion chamber, the less Nitrogen it uses. When a volume of 0.0005 $m^3$ is used, the amount of Nitrogen increases again but this might be due to another reason. The performance for the thruster using this size of combustion chamber is so bad for these opening times, that it needs more Nitrogen only to compensate for the large fluctuations in thrust; it waists a lot of Nitrogen.

For almost all cases it holds that when the minimum opening time is reduced, the amount of Nitrogen reduces as well, which can be explained by the fact that the thruster is functioning with greater precision. Only for a volume of 0.001 $m^3$ it does not hold; for this case only an increase in quality of microgravity is obtained. All these results have been summarised in Table 3.1.

TABLE 3.1 – Total mass of Nitrogen used for different values of combustion chamber volume.

| | M (kg) | |
|---|---|---|
| **Vc ($m^3$)** | **dt = 0,1 (s)** | **dt = 0,05 (s)** |
| **0,01** | 1,59 | 1.55 |
| **0,005** | 1,48 | 1.47 |
| **0,001** | 1,33 | 1,36 |
| **0,0005** | 1,96 | 1,41 |

It seems as though a volume of 0.001 $m^3$ is preferred, decreasing not only the amount of Nitrogen used, but also decreasing the dry mass. It would only be preferred, however, if the opening time of the valve could be reduced. But even with a minimum opening time of 0.05 s, the quality of the microgravity using a volume of 0.001 $m^3$ would not satisfy the stated boundary conditions. On top of this, it is unknown how the thruster will perform under even shorter opening and closing time. There is always a degradation of performance of the flow during start-up and these effects could have significant influence when the valve is opened and closed for even a shorter period of time. Since a thruster using a combustion chamber volume of 0.005 $m^3$ provides for a good quality of microgravity during the required amount of time, this volume was chosen. The fact that there is a limit on the minimum amount of opening time has no effect on the performance for this case since only a minimum amount of gain in used Nitrogen would be obtained when a faster reacting valve would be used.

In Figure 3.2 the thrust and the drag are shown as a function of time; they increases with time and the thrust is pulsed and varies around the drag. This behaviour is wanted because the thrust has to be equal to the drag. The maximum amount of thrust was taken to be 100 N, which would be reached after 48 s of flight. This means that at the end of this simulation, this level of thrust should be obtained. Fortunately, results appear to be consistent with the calculations made earlier because at the end of the simulation, the thruster is operating at maximum thrust: after 48 s, a thrust level of 99.45 N has been obtained with a chamber pressure of 19.9 bar.

It can also be concluded from the graph that as time progresses, the valve is opened more and more often. After ±45 s, the valve is fully opened and the thrust increases continuously. In the beginning when the valve is opened, a steep increase of thrust is produced and a slow decrease. The slow decrease is the result of a low chamber pressure that causes a low mass flow out of the thruster. More towards the end, the amount of thrust both increases and decreases rapidly and this is the result due to the higher chamber pressure.

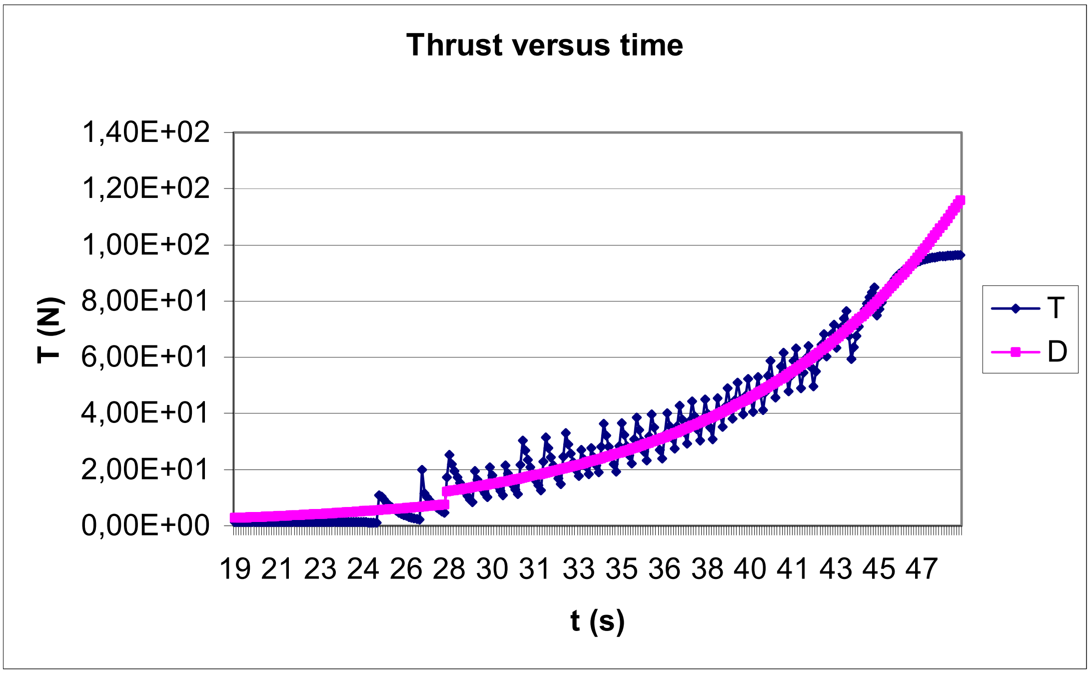



FIGURE 3.2 - Thrust versus time.

In Figure 3.3, the relative acceleration is shown, which should stay within the boundaries of ±0.001*g, or in other words $a_{rel}$ = ±1e-2 m/$s^2$. As can be seen from the graph, the obtained relative acceleration each time crosses this set boundary, although not with a great deal. A reason for this is the fact that the valve closes in 0.1 s and during this time, gas keeps on entering the combustion chamber. Pressure and thrust keep increasing and only in the next cycle this is corrected effectively; a time delay is introduced. So in order to account for this delay, the mass that flows into the combustion chamber should be stopped earlier.

However, although the quality of the microgravity environment has degraded a little, it can be maintained for 46.7 s, which is a good result.

An observation that is interesting to make is: why after 28 and 33 s, there is a larger increase in thrust and therefore a larger overshoot of the set boundary conditions for the relative acceleration.

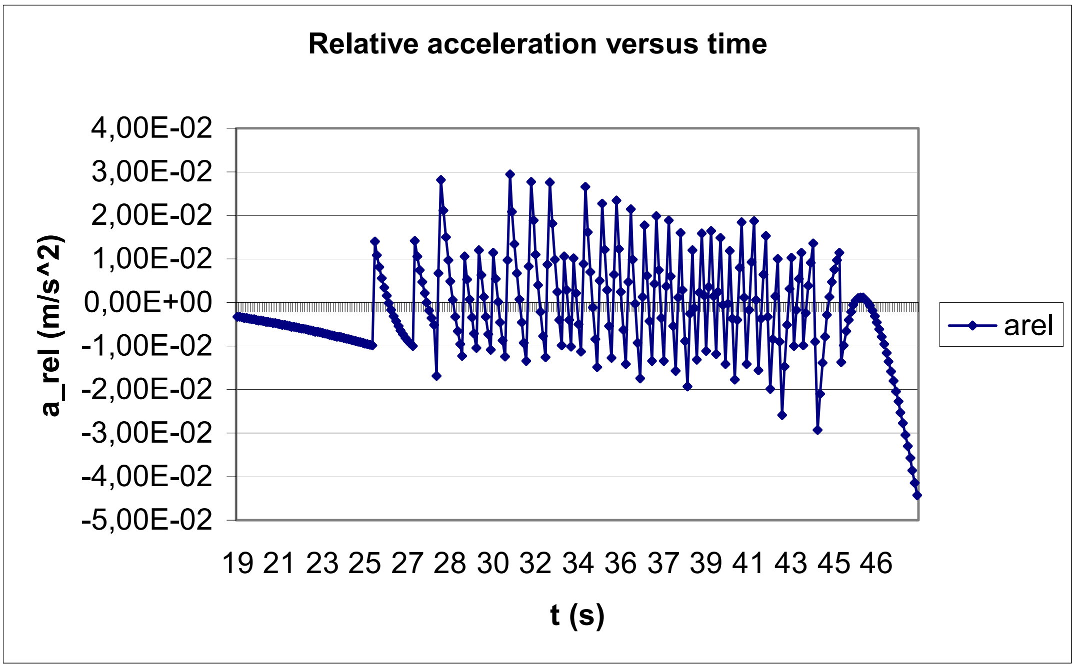



FIGURE 3.3 - Relative acceleration versus time.

A final option for the design of the thruster that could be considered is that the maximum level of thrust could be decreased by 50% and only 8 s of microgravity would be lost. However, since it was stated at the begin of the project that the thruster would be designed for a maximum level of thrust of 100 N, this option has been disgarded.

# CHAPTER 4

# TESTING THE THRUSTER

The objective of the tests was to see whether the thruster functioned as expected and to test the control system. Three tests were performed starting in vacuum and one test was performed at atmospheric pressure at 600 m altitude. If a prescribed trajectory for the thrust could be followed using some form of feedback, the microgravity environment could be assured in reality as well since the thruster acted according to its control.

In this chapter, several aspects of the test are discussed. In the first section, the experimental test set-up will be discussed, giving a broad idea of what the set-up looks like. Then the pressure losses will be explained and it is shown that they have a large impact on the results. Afterwards it will be described how the tests were controlled. Finally the results will be given and some conclusions will be drawn.

## 4.1 Experimental test set-up

The experiments have been performed in a test chamber supplied by INPE in Cachoeira Paulista. The chamber is 8 $m^2$ large and contains all the equipment necessary to perform the experiment. The thruster was connected, through a system of tubing, to a storage tank of Nitrogen, having a pressure of 100 bar and a volume of 5 liters. A pressure gauge was installed to measure the pressure of the combustion chamber and a balance measured the thrust. The outcomes have been read and saved in the command room, where the tests also were controlled.

*Feedback*

The thrust was used as a feedback indicator because it was then demonstrated that the amount of thrust could be controlled and a certain trajectory for the thrust could be followed. It would be preferred to use the relative acceleration as a feedback indicator since it will be used during the flight as well. However, this implies that the drag should also be known and this would introduce large errors since a lot of assumptions would have to be made to calculate the drag. Therefore, the thrust has been used as feedback because it introduces as little errors as possible since it is the most direct form of feedback.

*Increase in ambient pressure*

The ambient pressure inside the test chamber started at vacuum and increased during the test due to the expelled Nitrogen. The chamber has a volume of 8 $m^2$ and the total mass of Nitrogen that will be used is 1.48 kg. The thruster has been designed such that the temperature inside the combustion chamber is 293 K. This gives a total change of pressure inside the test chamber of :

$$\Delta p = \Delta \rho R T_e = \frac{\Delta m}{V} R T_e = 1.61 * 10^4 \ Pa \tag{4.1}$$

However, the change in atmospheric pressure during the flight will not be as large, only at lower altitudes will the atmospheric pressure increase faster. The values for the true atmospheric pressure have been taken from [9] and in reality, the atmospheric pressure only increases with $6.69*10^2$ Pa. However, equation (3.9) has been used to calculate the atmospheric pressure at each instance and when using this equation, an increment of atmospheric pressure of $1.50*10^4$ Pa is found. This means that the results of the test can be compared with the simulation but will be different in reality.

## 4.2 Pressure losses

*Feed system*

The feed system of the experimental test set-up contains following parts (and are given in the order of appearance):

(1) A relief valve that connects the tanks to the tubes
(2) A piece of tubing of 40 cm long, with a diameter of 3/8 inch
(3) A piece of tubing of 6 m long, with a diameter of 1 inch, containing 2 large bends
(4) A piece of tubing of 2.5 m long, with a diameter of 1/2 inch, containing 2 large bends
(5) A ball valve that is opened or closed according to the requirements

Since Nitrogen is used as propellant, no filter is needed because the gas is inert and so it does not react with the piping, not leading to any impurities. Also, the feed system does not include a pressure regulator since this would make it impossible to reach the amount of mass flow required. This means that the mass flow during the experiment will not be constant and will decrease as time passes.

The pressure loss that is obtained due to this part has been calculated in the following way. Since there is no pressure regulator, the gas will have the same pressure as in the tank, disregarding the pressure loss. So the density of the gas was calculated using the pressure inside the tank:

$$\rho = \frac{p}{RT} = \frac{100 * 10^5}{296.8 * 293} = 114.93 \ {}^{kg}\!/_{m^3} \tag{4.2}$$

Now using the required mass flow of 0.1359 kg/s, the velocity for each part could be calculated:

$$V = \frac{m}{\rho A} \tag{4.3}$$

The Reynolds number was calculated in order to identify if the flow in the tubing is laminar or turbulent, leading to a larger or smaller pressure loss respectively. To do so, a dynamic viscosity of $1.7*10^{-5}$ Pa [10] was used:

$$\mathrm{Re}_D = \frac{\rho V D}{\mu} \tag{4.4}$$

The flow through the entire feed system was found to be turbulent, having a Reynolds number in the range of 2 - $7*10^5$ in the tubing. This means that the following expression has to be used to calculate the friction factor for the tubing:

$$f = 0.316\left(\frac{1}{\mathrm{Re}_D}\right)^{0.25} \tag{4.5}$$

The flow in the valves will be considered to be fully turbulent. Therefore, a different expression is used for the valves, which takes into account the roughness of the pipes. For the value of the roughness, e, a value of 0.05 mm has been used, corresponding to a value of stainless steel [8].

$$f_T = 8\left(2.547\ln\left(3.707\frac{1}{\frac{e}{D}}\right)\right)^{-2} \tag{4.6}$$

Finally, the pressure loss for the tubing and the valves and bends can be calculated with the following equations respectively:

$$\Delta p = f\frac{L}{D}\frac{1}{2}\rho V^2 \tag{4.7}$$

$$\Delta p = f_T\frac{L_{eq}}{D}\frac{1}{2}\rho V^2 \tag{4.8}$$

where the values for the equivalent length have been taken from [8]. The results of the calculations have been summarised in Table 4.1:

TABLE 4.1: Pressure loss for different components of the feed system.

| | L or Leq (m) | ID (m) | f | fT | delta p (Pa) |
|---|---|---|---|---|---|
| **Relief valve** | 13 D | 6,35E-03 | - | 4,54E-02 | 4,73E+04 |
| **Rigid tubing** | 0,04 | 9,53E-03 | 1,07E-02 | - | 7,11E+02 |
| **Rigid tubing** | 6 | 2,54E-02 | 1,37E-02 | - | 1,01E+03 |
| **Rigid tubing** | 2,5 | 1,27E-02 | 1,15E-02 | - | 1,13E+04 |
| **4 bends** | 16 D | 1,27E-02 | - | 2,83E-02 | 1,84E+03 |
| **Ball valve** | 18 D | 6,35E-03 | - | 3,50E-02 | 3,65E+04 |

This leads to a total pressure loss of 0.986 bar. Now assuming that the pressure loss only affects the density and not the velocity of the Nitrogen, a mass flow of 0.1346 kg/s is obtained at the end of the tube, instead of 0.1359 kg/s. This means that instead of 46.7 s of microgravity, 46.6 s of microgravity can be maintained, meaning that it has hardly any effect on the performance of the thruster.

*Storage system*

During the experiment the pressure in the storage tank decreased, leading to a decrease in mass flow as well. As described before, there was one tank available, having a volume of 5 $m^3$ at atmospheric pressure and it stored the Nitrogen at 100 bar. This meant that a total of 5 kg of Nitrogen was available. It was calculated that a total amount of 1.48 kg of Nitrogen was needed to perform the test. This led to a decrease in mass of Nitrogen, and so a pressure decrease, of 29.6%. Taking into account this pressure decrease during the experiment, a mass flow at the end of the experiment was found to be 0.1078 kg/s. With this value for the mass flow, a microgravity environment of 44.7 s could be maintained.

## 4.3 Control system

A control system was needed since the opening and closing time is not constant during the flight. This control system consisted of two main parts: the hardware was a data acquisition driver provided by National Instruments, NI-DAQ, and a software program that communicated with the hardware. The software was developed using C++, using a Borland compiler [11]. It is schematically explained by Figure 4.1 and can be found in Appendix C.

First of all, it has to be marked that the program does not operate in real time. The program does wait until 0.1 s has past, but this timing is not exact. If the program could be run under DOS, this performance would increase. However, due to the fact that information that is needed in order to communicate with the hardware is written for windows applications, it is not possible to run the program under DOS or Linux. This meant that there was a delay of 0.01 s in the commanding operation of the program.

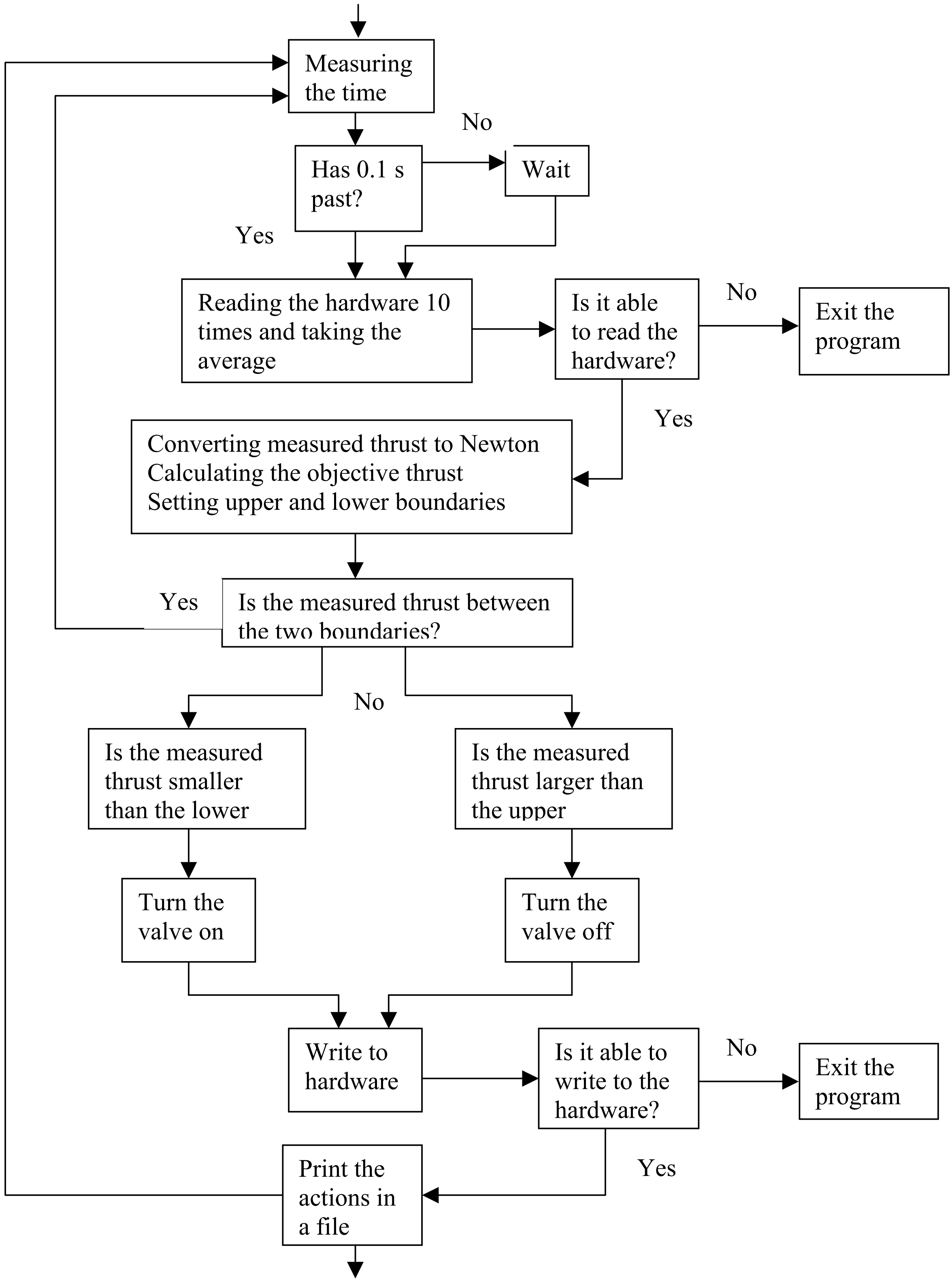



FIGURE 4.1 – Block diagram of the control system.

As discussed in Section 4.1, it was the objective to follow a thrust trajectory that corresponded as close as possible to the thrust trajectory that will be followed in reality. This trajectory was found by analysing the results of the simulation and is a function of time. In the control program, the time was used to calculate the objective thrust for each time step using this thrust trajectory. The measured thrust was compared with the objective thrust and actions were taken accordingly.

In the simulation boundary conditions were set for the maximum allowable relative acceleration. As explained in Section 4.1, the thrust was used as feedback and so the boundary conditions that created a microgravity environment had to be translated from acceleration to a force. This has been done by multiplying the maximum allowable relative acceleration with the mass of the platform and this has led to a discrepancy between the required thrust and allowable thrust of 4.35 N. This meant that the measured thrust should stay within a region of $T \pm 4.35$ N, with a maximum and minimum value respectively.

When this value of 4.35 N was translated to an amount of volts, the result came out to be 0.3 V. Only a small error in the measured value would therefore lead to wrong decisions. In order to solve this problem, the thrust is measured 10 times and the average is taken to filter out any errors. Errors might occur due to vibrations in the measuring device that are the result of acoustic vibrations or vibrations due to combustion. The fact that no combustion process takes place reduces the amount of vibrations considerably. However, this measure of debouncing has been introduced as an extra precaution.

A second precaution has been taken by exiting the program when the software is not able to communicate with the hardware.

The hardware and the software have been subjected to several test cases and all test cases were passed successfully. They are summarised in Table 4.2:

TABLE 4.2 – Test cases performed.

| | | Hardware | Software | Bench test |
|---|---|---|---|---|
| **Input** | | X | X | x |
| **Output** | | X | X | x |
| **Logic** | **- From on to off** | | X | x |
| | **- From off to on** | | X | x |

## 4.4 Results of the tests

Three tests were performed starting in vacuum and one test was performed at atmospheric pressure at 600 m altitude. First only the results will be discussed using only the first test and a comparison will be made between the simulation and the results of the first test. This comparison is made using only the first experiment since each time the mass flow into the combustion chamber has decreased considerably and so the results of the first test are the most representative. Afterwards the difference between the different tests will be discussed.

In Figure 4.2 the thrust that was measured during the first test is plotted versus the time. Also the required, or calculated thrust has been plotted.

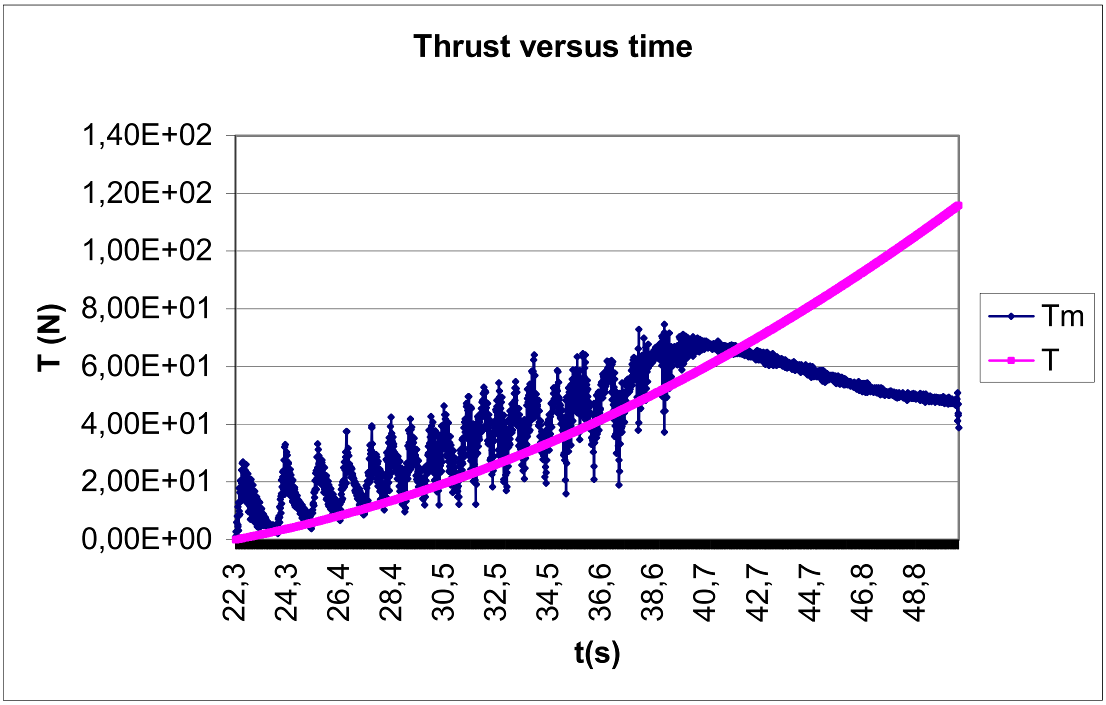



FIGURE 4.2 – Results of the first test: thrust versus time.

The maximum amount of thrust obtained is 68 N, instead of a required 100 N and this can mainly be explained by two causes (of course the other assumption that have been made have an effect as well, however, these effects are considered to be smaller). The first one was due to an error in assembly. A temperature gauge could be installed to measure the temperature of the combustion chamber. However, it was decided not to measure the temperature and unfortunately, the hole was not closed. This led to an outflow of gas in opposite direction, resulting in a smaller amount of thrust due to a pressure loss and to a counteracting force that was also measured by the thrust balance.

The second, and more important reason, is that the mass flow was smaller than required. The reduction was mainly caused by the reduction in tank pressure during the experiment. This will be proved later in this section, using the figure of combustion chamber pressure.

What can also be seen is that the measured thrust is almost always larger than the required thrust, except at the end when the measured thrust is decreasing again. It appears as though the thruster is not following the commanded thrust-curve. However, this is not the case and it can be explained by the fact that the thruster was not commanded in real time. The control program had difficulties when several tasks had to be commanded at the same time and this resulted in a non-continuous time line used by the control program. It was described before that the program ran under windows, already introducing a delay. But this was a constant delay. However, when several tasks had to be executed, the computer turned out to be not fast enough to handle all the tasks, not giving a command every 0.1 s as wanted. This resulted in large 'jumps' in time, which led to a non-continuous time line. Since the calculated thrust was depended on the time, large jumps in required thrust were introduced as well. Since the measured thrust should approach the required thrust as close as possible, the resulting measured thrust turned out to be larger as well. In the figure above, a continuous time line has been used (giving an impression of how the required thrust should actually be). Since the thrust obtained during the test always had to approach the required thrust as close as possible (and thus having a larger value), it looks as though the measured thrust is always larger than required.

However, when the time line is used to plot the results that has been used by the control program, the Figure 4.3 is obtained. It shows the jumps in calculated thrust and more important, that the measured thrust does, up to 42 s, indeed follows its commands. After 42 s, the measured thrust only decreases while the thruster is fully opened. This can be explained by the fact that the mass flow is only decreasing, resulting in a decreasing thrust. This implies that the situation of the thruster functioning with a fully opened valve should be avoided when a blow-down system is used since only more mass is expelled while the thrust-level decreases.

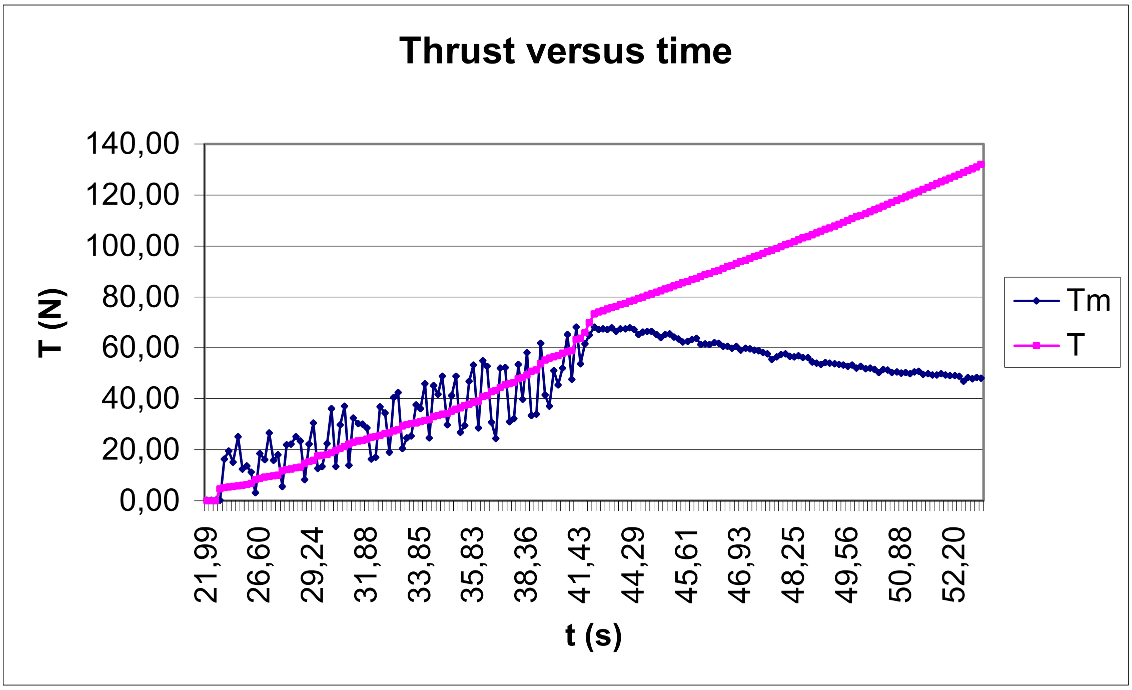



FIGURE 4.3 – Results of the first test: thrust versus time using a non-continuous time line.

When the relative acceleration was determined, by subtracting the required thrust from the measured thrust and dividing it by the mass of the platform, the result shown in Figure 4.4 was obtained. (A continuous time line was used.)

The quality of the microgravity environment seems to be lacking, however, it was expected since the relative acceleration is derived from the thrust. Due to the large jumps in time, and thus calculated thrust, the measured thrust is always larger than the actual thrust, or in other words, the thrust is always larger than the drag. This gives a positive value for the relative acceleration. (If the time line, used by the control program, was used to plot the figure, the relative acceleration would be around 0.)

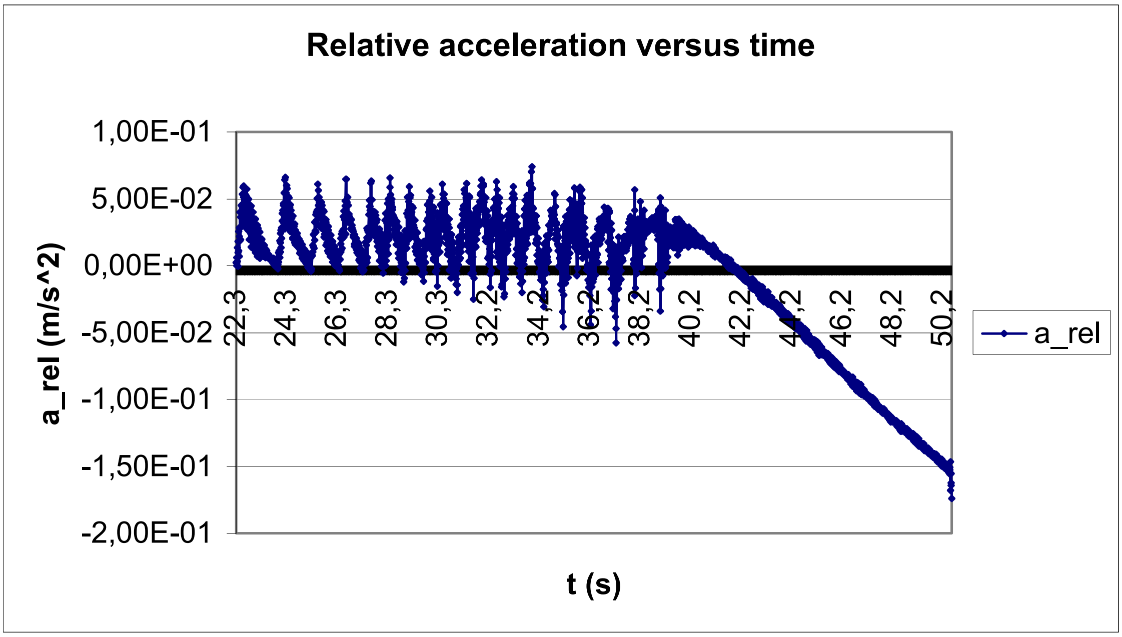



FIGURE 4.4 – Results of the first test: relative acceleration versus time.

Also, the relative acceleration does not stay between the boundary conditions of 0.001*g. This might be explained by the fact that the thruster is always opened for a longer period of time in order to approach the calculated thrust (that is increasing faster than it should). More gas flows into the combustion chamber and a larger pressure build-up is reached. A similar dynamics as for thrusters having a smaller combustion chamber volume, might be the reason of the overshoots.

The results for the obtained chamber pressure have been plotted in Figure 4.5. A maximum chamber pressure of 16 bar has been reached, even though a maximum pressure of 20 bar was wanted. This loss in pressure can be explained by the fact that mass flow into the combustion chamber is considerably lower than designed for due to the tank pressure loss. If the simulation is run using a mass flow of 0.1078 kg/s (as calculated in section 4.2), also a maximum chamber pressure of 16 bar is obtained. So the results shown in figure 4.5 were exactly as predicted, however, unwanted.

The chamber pressure is even further degraded by the fact that the thruster has been opened for more longer periods of time due to the larger calculated thrust, leading to a slightly smaller maximum pressure as well.

After 40 s, the pressure decreases again and this resulted in a decreasing amount of thrust as well. This loss in pressure might be due to a decrease in mass flow, since it is known that from that moment on, the valve was completely opened.

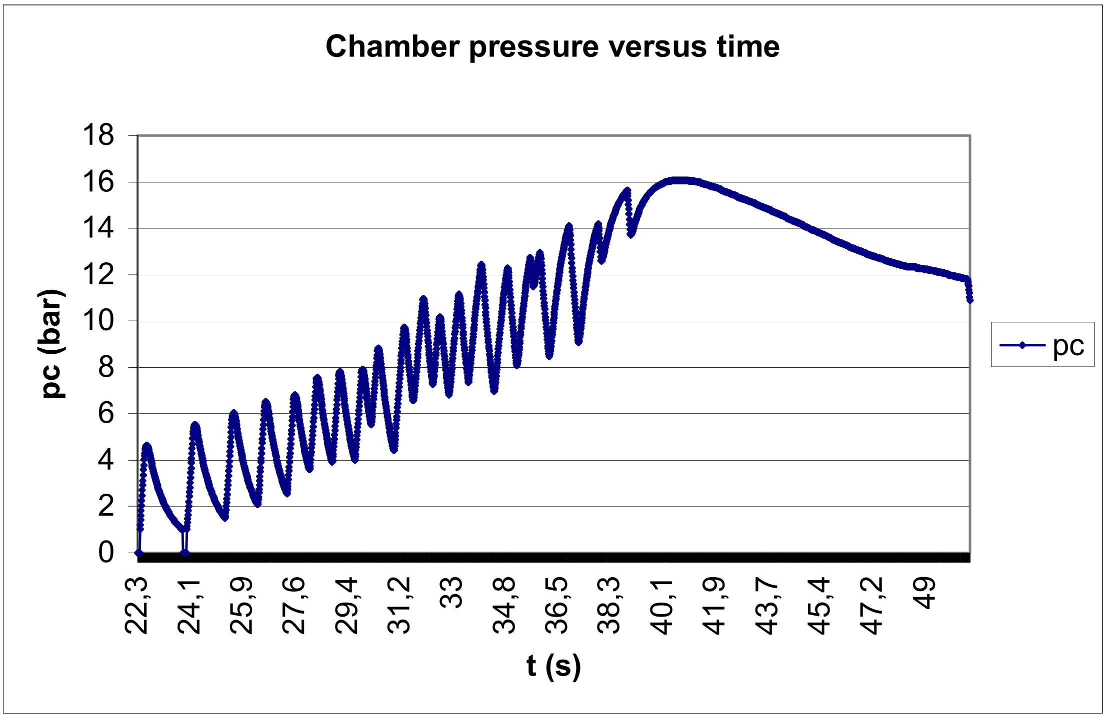



FIGURE 4.5 – Combustion chamber pressure versus time.

Finally, in Figure 4.6, all the different thrust-levels found during the different tests have been plotted and it also shows some interesting results.

The fourth test had been performed with an atmospheric pressure at an altitude of 600 m. The thruster was not designed to perform at this altitude and it can be seen that the atmospheric pressure is too large. The over-expansion of the flow leads to shockwaves that bounce inside the nozzle, giving only large fluctuations in the thrust-level. The flow, however, is supersonic because the critical pressure ratio has been reached.

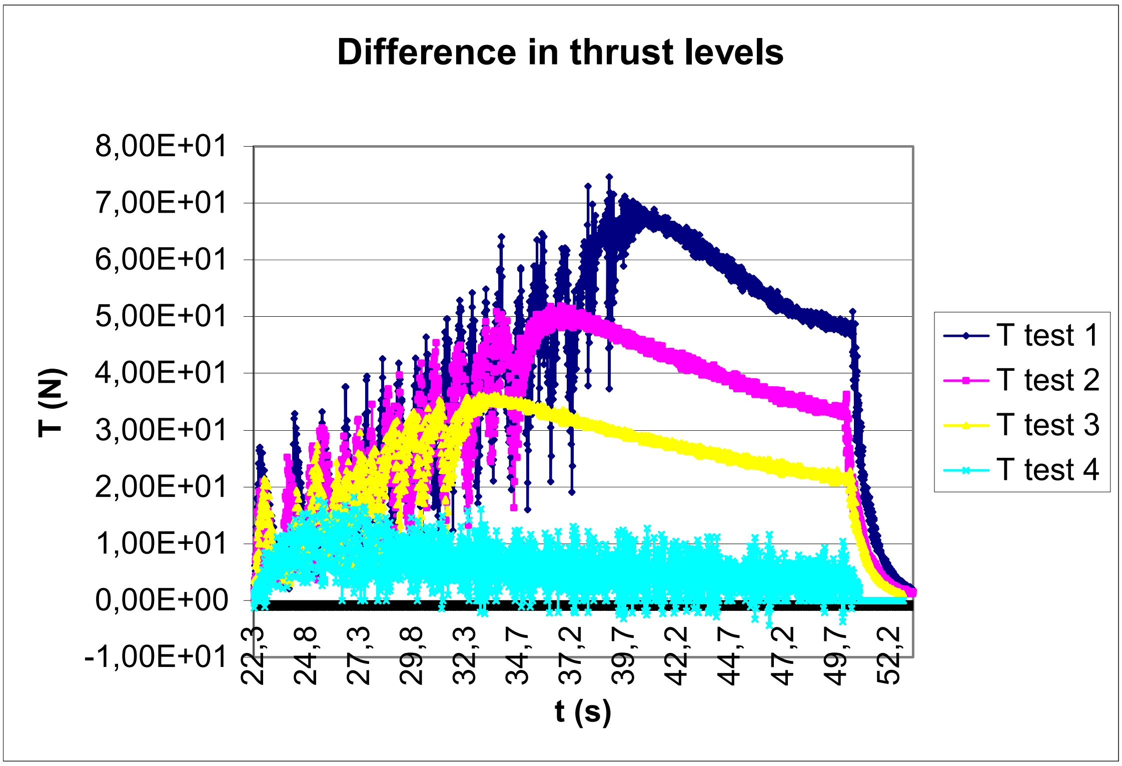



FIGURE 4.6 - The difference in thrust-levels for different tests.

A second observation that can be made is that the maximum level of thrust is found each time earlier during the test. What was shown earlier, is that the thrust-level only decreases, once the valve is fully opened. The mass flow has decreased for each subsequent test, leading to a smaller pressure build-up in the combustion chamber. The required thrust-level is equal for all cases, so the thruster had to be fully opened earlier and for a longer period of time to produce the same level of thrust. This has led to a maximum level of thrust earlier during the test.

A final observation is that the difference between the first and second test is larger than the difference between the second and the third test. This can be explained by the fact that the hole, caused by a missing temperature gauge, was closed after the second test, not leading any longer to a loss in pressure and thrust.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

In this report, a thruster has been designed and tested and the results of this study can be used for future missions. Some conclusions can be drawn and for a following project some changes might be implemented.

The main conclusion that can be drawn from the observations during the design process is that a maximum thrust of 100 N is large value when using a cold gas system. The dry mass of the system and the total mass of Nitrogen could be reduced significantly if the maximum amount of level of thrust would be reduced. A maximum level of thrust could be decreased by 50% and only 8 s of microgravity would be lost. The mass flow that was required for this thruster was also very large and it was difficult to reach this mass flow during testing. A smaller thruster with a smaller mass flow would therefore also lead to an easier system to test with a higher performance.

An important conclusion that can be made from observations during testing is: when possible, a blow-down system should be avoided. It was shown that the maximum level of thrust was reduced by 30% during the first test due to a loss in mass flow using the configuration described in this report. If a smaller thruster was used, the amount of Nitrogen needed would be reduced. Also, when the same size tank was used, this would lead to a smaller decrease in the amount of mass flow. However, some form of pressure regulation is preferred since it will increase the performance of the thruster considerably.

A third conclusion that can be drawn is that the control system used by the thruster should be improved for testing. The control system was not able to handle all the tasks and a faster system should be designed, preferably running under DOS or Linux. During the flight this problem will be circumvented since the feedback system is not dependent on time anymore. A direct feedback will be given using the relative acceleration.

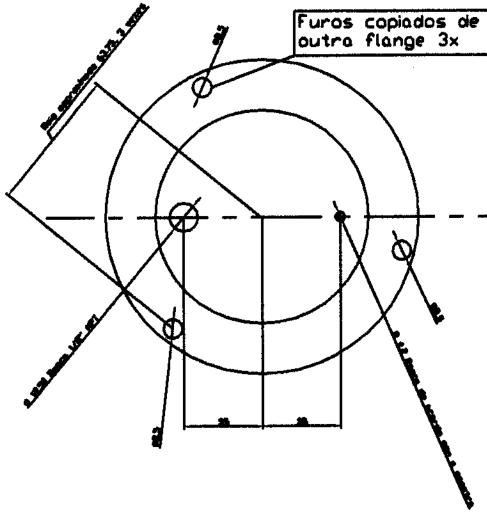
The minimum opening time of the valve was a limitation in the design process. It was stated in chapter 3 that a faster valve would reduce the dry mass of the system, as well as the total amount of Nitrogen. In the case that the mass of the platform becomes a critical design factor, a faster valve might be considered in order to reduce the mass of the propulsion system. However, some tests should be performed to see how the gas reacts under even shorter opening time of the valve and some reduction in performance might occur. A valve with proportional control might also be considered. In conjunction with a buffer tank it should provide a smooth control for the thrust.

In spite of all the assumptions that have been made, the results turned out to be very consistent with the theoretical results. The tests gave a lot of insight in the processes that occur and it even validated some assumptions and speculations. Although still many improvements can be made, this project turned out to be successful.

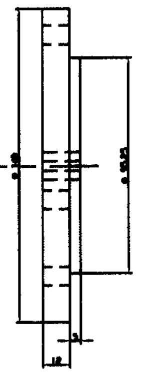
# REFERENCES


1. Milani, P.G.; et al. **Sistema da plataforma suborbital – PSO**. São José dos Campos: INPE, Feb. 2000.
2. Furlan, B.M.P. **Projecto micro-gravidade:** plataforma Mikroba, configuração e trajetória. São José dos Campos, INPE, Jan. 2005.
3. Rand, J.L.; Fuchs, M.; Kretzschmar, K. A microgravity testbed, **Advances in Space Research,** v.13, n.2, p.177-180, Feb. 1993.
4. De Groot, W.A**. Propulsion options for primary thrust and attitude control of microspace-craft**. Washington: NASA, 1998. (NASA/CR-1998-206608).
5. National Institute of Standards and Technology. Chemistry web book. 2003. Available from: http://webbook.nist.gov/chemistry. Visited: 28 Apr. 2005.
6. Pardue University. Fundamental properties of internal fluid flows. Available from: http://engineering.purdue.edu/AAE/Research/Propulsion/Info. Visited: 28 Apr 2005.
7. Cornelisse J.W., Schöyer H.F.R., Wakker K.F. **Rocket propulsion and spaceflight dynamics.** London: Pitman, 1979. 505p.
8. University of California Santa Cruz. Santa Cruz Institute of Participle Physics. The standard atmosphere. Available from: http://scipp.ucsc.edu/outreach/balloon/atmos/1976% 20Standard%20Atmosphere.htm . Visited: 28 Apr. 2005.
9. Public Domain Aeronautical Software. Properties of the U.S. Standard Atmosphere 1976. Available from: http://www.pdas.com/atmos.htm . Visited: 28 Apr. 2005.
10. Equivalent lenght of pipe bends. 2003. Available from: http://dutlsisa.lr.tudelft.nl/Propulsion_details/Data/Feed_systems.htm. Visited: 28 Apr. 2005.
11. Kernighan B.W., Ritchie D. **The C programming language.** 2.ed. Englewood Cliffs: Prentice Hall, 1988. 272p.

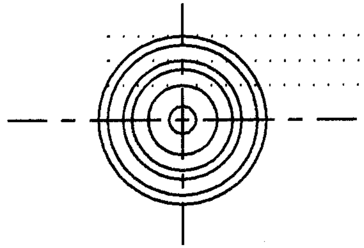
# APPENDIX A



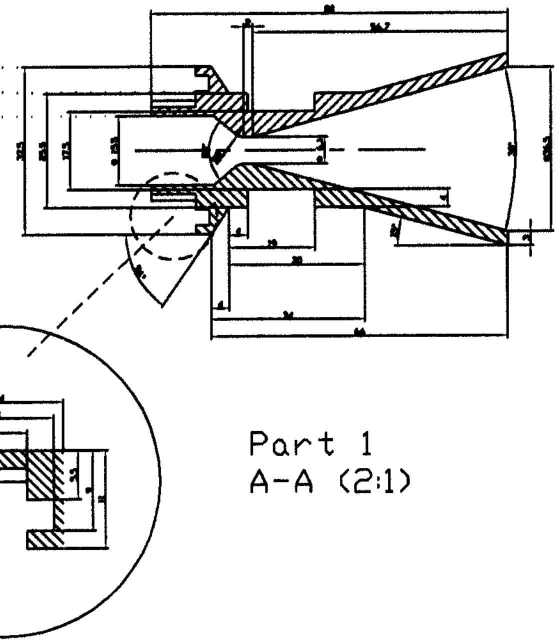

Front view
Part 3
(1:1)



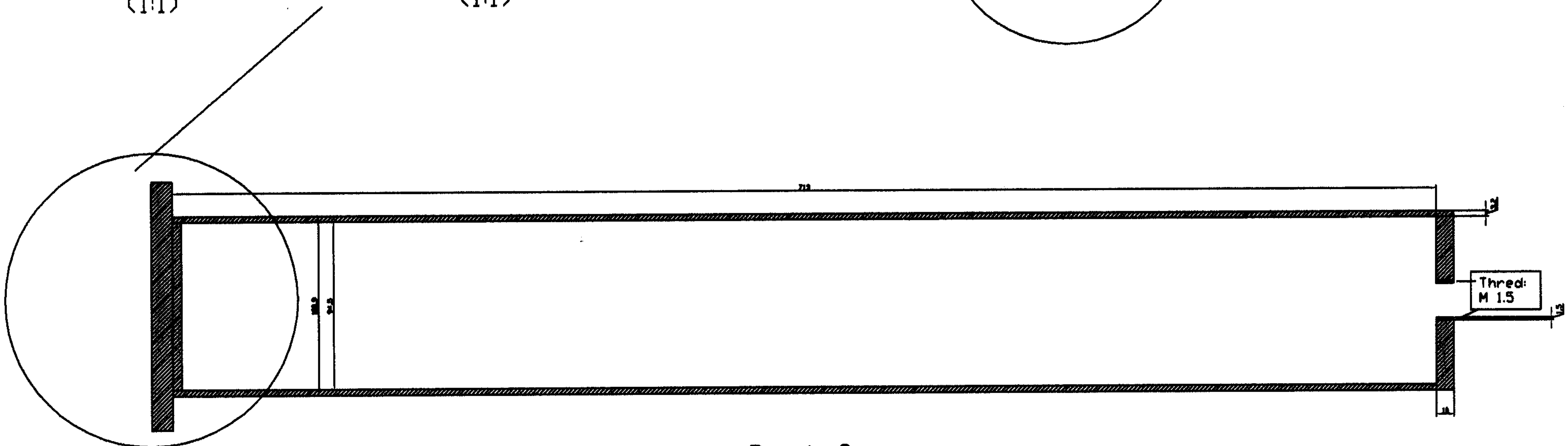
Side view
Part 3
(1:1)



Front view
part 1
(2:1)




Part 1
A-A (2:1)




Part 2
B-B (1:1)

# APPENDIX B

```
clc
clear

% Parameters of the thruster and the platform
m = 443;
S = 0.159;
g = 9.81;

mmax = 0.1359;
Ae = 0.0011;
At = 2.9121e-5;
cstar = 428.5696;
R = 296.7987;
Tc = 293;
gamma = 0.6881;
ratio = 1.42;
constant = gamma^2/(36^2*2*ratio/(ratio-1));

% Input parameters
Vc = 0.005;
threshold = 1e-3;
dt = 0.1;

% Initial conditions
pc = 2.997e+2;
p0 = 1e+5;
a0 = 9.81;
V0 = 0;
h0 = 42e3;
rho0 = 1.225;
dp_dt0 = 0;
mout = pc*At/cstar;

for t = 0 : dt : 48
    V = V0 + a0*dt;
    M = V/340;
    h = h0 - V*dt;
    rho = rho0*(9.78261e-1 + h/201010)^(-35.16319);
    pa = p0*exp(-1.225*g*h/p0);
    pe = constant^(ratio/2)*pc;
    cF = gamma*sqrt(2*ratio/(ratio-1)*(1-(pe/pc)^((ratio-1)/ratio)))+(pe/pc-pa/pc)*Ae/At;

    if M < 0.8
       cD = 0.25;
    elseif M > 0.8 | M < 1.5
     cD = 0.4;
  elseif M > 1.5
```

```
    cD = 0.35;
  end

  D = 0.5*rho*V^2*cD*S;
  T = pc*cF*At;
  a_rel = (T-D)/m;

  if a_rel < threshold*g & dp_dt0 > 0
    min = mmax;
  elseif a_rel >= threshold*g & dp_dt0 > 0
    min = 0;
  elseif a_rel > -threshold*g & dp_dt0 < 0
    min = 0;
  elseif a_rel <= -threshold*g & dp_dt0 <= 0
    min = mmax;
  else min = 0;
  end

  % Finding new amount of pressure in chamber
  dp_dt = R*Tc/Vc*(min - mout);
  p = pc + dp_dt*dt;

  T = p*cF*At;
  a = (T-D)/m + g;
  mout = p*At/cstar;

  if p <= pa
    mout = 0;
  end

  dp_dt0 = dp_dt;
  pc = p;
  a0 = a;
  V0 = V;
  h0 = h;

  fprintf('%2.1f     %3.3f  %3.3f  %3.3f  %3.3f\n', t, min, a_rel, T, D)
end
```

# APPENDIX C

```
// This program reads the measured thrust (the input signal) and the time. An objective
// thrust curve has to be followed, and the objective thrust is calculated using the time.
// Then the two are compared and depending on whether the measured thrust is smaller
// or larger than the objective thrust, the valve is turned on or off (your output signal).

# include <windows.h>
# include <stdlib.h>
# include <stdio.h>
# include <math.h>
# include <time.h>
# include <condefs.h>
# include <wdaq_c.h>

//---------------------------------------------------------------------------
USELIB("..\..\..\NIDAQWin95\lib\nidaq32b.lib");
//---------------------------------------------------------------------------

     void Execute_AI_VRead();
     void Execute_AO_VWrite();

// Determining time
int main(void)
{

  FILE *fid;

  // Define variables
     i16   err,
           device = 1,
           ch = 0,
           gain = 1,
           m, n;
     f64   valve,
           Tm_volt, soma, av,
           Tm,
           T, T_l,T_u,
           t, t0, t1, t_help, dt;

  // Start the clock & opening the file
  t0 = (float)clock();
  dt = 0.099*CLOCKS_PER_SEC;
  fid = fopen("output.txt", "w");
  valve = -4.5;

  // Starting the loop
  for (n = 0; n <= 480; n++)
  {
```

```
while (((t1 = (float)clock())-t0) < dt)
;
t =  clock()/CLOCKS_PER_SEC;

// Input; reading the hardware
soma = 0;
for (m = 0; m <= 9; m++)
{
	err = AI_VRead(device,ch,gain,&Tm_volt);
	if (err != 0)
	{
		fprintf(stderr, "The system is unable to read the input\n");
		getchar();
	}
	soma = soma + Tm_volt;
}
av = soma / 10;

// Calculating the measured thrust and the objective thrust
Tm = 31.56*av – 10.61;
t_help = pow(t,2);
if (t < 22.3)
{
	T = 0;
}
else
{
	T = 0.08579*t_help - 2.136*t + 5.0196;
	T_l = T - 4.35;
	T_u = T + 4.35;
}

if (!(Tm >= T_l && Tm <= T_u))
{
	// Defining the logic
	if (Tm < T_l)
	{
		valve =  -4.5;
	}
	else if (Tm > T_u)
	{
		valve = 4.5;
	}

	// Output; writing to the hardware
	err = AO_VWrite(device,ch,valve);
	if (err != 0)
```

```
        {
            fprintf(stderr, "The system is unable to write the output\n");
            getchar();
            exit(2);
        }

        // Saving data
        if (fid == NULL)
        {
            fprintf(stderr, "It is not possible to access output.txt\n");
            getchar();
            exit(3);
        }
        fprintf(fid,"%4.2f      %8.3f      %8.3f        %8.3f\n", t, Tm, T, valve);
    }
    else
        ;
    t0 = t1;
  }
  fclose(fid);
  valve = -4.5;
  return 0;
}
```