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Pressurization system for a cryogenic propellant tank in a pressure-fed high-altitude rocket

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Abstract
For the usage of liquid oxygen as a propellant in pressure-fed rocket engine systems, the propellant needs to be pressurized, for example by using an inert gas such as helium. This paper describes a practical investigation with measurement results on the pressurization and expulsion of liquid nitrogen from a 30 L pressure vessel at 30 bar. The amount of helium needed and the effect of the injection method on this amount is investigated by numerical simulations that are validated using experimental test results. The collapse factor for the system is determined. It is concluded that axial injection of the gas is more advantageous than the commonly used radial injection.

1. Introduction

This paper describes the practical investigation of a simple, low-cost pressurization system for a small, high-pressure, cryogenic propellant tank. The pressurization system is developed for high-altitude sounding rocket applications by the student society Delft Aerospace Rocket Engineering (DARE) of Delft University of Technology. DARE has the aim to be the first student society in the world to launch a rocket into space with a self-designed rocket engine. For the next generation of DARE high altitude rockets, DARE initiated the cryogenic project to investigate the usage of cryogenic propellants, most specifically liquid oxygen.[12]

For the design of a sounding rocket using liquid oxygen a tank pressurization system needs to be designed, as DARE does not yet have experience with propellant pumps. It has been chosen to investigate a system using pressurized helium. The helium is initially stored in a separate, high-pressure tank. During operation a pressure regulator allows helium to flow into the propellant tank ullage as it empties, maintaining a (near) constant pressure in the propellant tank. The helium tank takes up a significant volume within the rocket because the propellant tanks need to be operated in the pressure range around 30 bar (due to minimum combustion chamber pressure) and helium tank pressure cannot be much higher than 200 bar (due to operational and structural constraints). Initial sizing estimates put the length of the helium tank near 20% of rocket length, and the helium tank mass near 6%. The mass of the helium itself is negligible (<1%). Because of the large influence the helium tank has on the system sizing, it is needed to determine the amount of helium required as exact as possible.

The goal of the present investigation is to determine the amount of pressurant gas required for pressurized expulsion of the propellant, and to investigate the effects of different types of pressurant injectors. As a practical goal it was chosen to see if the collapse factor could be determined to within 10% accuracy by numerical simulations. Various 1D simulations are created and evaluated. These simulations are then validated with a practical test setup. Cryogenic propellant pressurization and the effect of different pressurant injectors has been investigated in the past.[5] However these investigations often focused on low pressure (P < 10 bar), high volume (V > 200 L) tanks, while high pressure, low volume tanks are of interest in the investigation. Because of the effects of higher pressures and scale changes on heat transfer it is hypothesized that axial injection of the pressurant will be more beneficial for pressurant gas consumption in high-pressure, low-volume tanks compared to the commonly used radial injection method. Furthermore it is hypothesized that the usage of pressurant gas can be reduced even further by splitting the pressurant gas stream by means of a vortex tube (or "Hilsch tube"[7]) into a cold and a warm gas stream.

Section 2 gives a short theoretical background. The different injection methods are explained in section 3. The simulation efforts to attempt to simulate the process are described in section 4. Section 5 describes the practical test setup and the way in which the tests were conducted. The measurement results are given in section 6. These are then

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compared with the simulation results in section 7. Sections 8 and 9 give the conclusion, recommendations and the acknowledgements.

2. Tank collapse factor

The total mass of helium needed for a pressure regulated system can theoretically be determined by means of equation 1.

$$m_0 = \frac{P_u V_{prop}}{RT_0} \left(\frac{\gamma}{1 - P_{pres}/P_0} \right) \tag{1}$$

In this equation m_0 is the total mass of helium needed, P_u is the pressure in the ullage volume (and thus in the propellant tank), V_{prop} is the volume of the displaced propellant, R is the specific gas constant of the pressurant gas used, T_0 is the initial temperature of the pressurant gas, P_{pres} is the desired final pressure in the pressurant tank and P_0 is the initial pressure of the pressurant. This equation is due to Sutton[10] and Ring[9] and assumes ideal gas*, no heat transfer and no mass transfer.

It is however proposed that for the specific case under investigation, heat transfer is of more significance on the amount of helium required than in the gas of large pressure-fed systems. This is reasoned because of four factors that all increase heat transfer between gas and wall. These are: (1) The high pressure in the tank. (2) The large temperature difference between 'warm' pressurant gas and cold propellant and cold propellant tank wall. (3) Large area to volume ratio of the ullage due to small diameter of the rocket. (4) Large heat capacity of the propellant tank, because of its thick walls and bulkheads, designed to withstand the high pressures.

The influence of heat transfer and other effects can all be combined into the collapse factor. The collapse factor K is defined as the ratio of the real amount of gas flowing into the propellant tank versus the ideal amount of gas needed to flow in.[4] The ratio is given by equation 2.

$$K \equiv \frac{(m_u)_{real}}{(m_u)_{ideal}} \tag{2}$$

In this equation m_u is the gas mass flowing into the ullage. The ideal amount is gotten by means of a mass balance, the isentropic relations, and equation 1. These combined result in equation 3.

$$(m_u)_{ideal} = m_0 \left[1 - \left(P_{pres}/P_0 \right)^{\gamma} \right] \tag{3}$$

De Quay and Hodge[4] present an excellent overview table of experimentally determined collapse factors collected from literature from around 1966 till 1998. From their data it is clear that most tests conducted in the past were for large tanks (ranging from 100 L to 40 m^3), and relatively low pressures (in general around 3.5 bar). Collapse factors for liquid oxygen or liquid nitrogen pressurized with helium range approximately between 1 and 2. This range already means a large uncertainty on the amount of helium required, while it is not even sure that any of these cases can be seen as good representatives for the case under study here. The data presented by De Quay and Hodge also highlights the scarcity in experimental data on collapse factors available.

The uncertainty in the collapse factor, the scarcity of data, and the expectation that heat transfer is of more importance in the pressure-fed cryogenic sounding rocket case, all contribute to the motivation for the current research.

3. Pressurant injection methods

Pressurant gas is injected into the propellant tank by means of a pressurant injector, sometimes called pressurant diffuser. The method of injection determines the speed and direction with which the pressurant flows into the propellant tank. This can be of major influence on the collapse factor.[4]

The most common type of injection is the radial injection method.[8] In this case gas is injected radially along the top bulkhead. The gas flow pattern is shown schematically on the left of figure 1. The injection can possibly happen via a sintered metal element to allow for slow diffusion of the gas into the chamber. The idea behind radial injection is that the gas does not disturb the liquid surface and thus does not loose heat to, and does not dissolve into, the propellant.

The opposite method is axial injection, where gas is blown in parallel to the tank axis via a simple open port. This is shown in the middle of figure 1.

An important paper on the subject of pressurant injection methods is the NASA technical note by DeWitt, Stochl and Johnson on the effect of different pressurant injectors on pressurant gas usage.[5] The paper by DeWitt et al. is of

*Ring tries to correct for some non-ideal gas effects by multiplying the pressure ration in the denominator by the compressibility factor Z_0([9]). It was however found that this can introduce large errors when the pressurant tank is bigger than strictly necessary because then pressure in the pressurant tank hardly drops during operation and thus $Z_0 P_{pres}/P_0 \approx 1$.

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particular interest for this research as it is the only paper that could be found that is focussed on the effect of injection methods. The note describes tests of six types of injector geometries. They also conducted tests with a tank of similar scale as what is proposed in this research, however tests were conducted with liquid hydrogen as propellant and gaseous hydrogen as pressurant. Their results indicated that a straight tube injector resulted in the least amount of pressurant required. They attributed this to (1) the evaporation of propellant when it came in contact with the pressurant gas and (2) the radial temperature profile created by this injector, where the temperature gradient meant the gas was warm at the tank centreline and cold near the walls. The cold gas temperatures at the wall resulted in low heat transfer from gas to the wall, and so to lower pressurant requirements.

From this it is conjectured that also in the case of liquid oxygen pressurization with helium for small-scale pressure-fed rockets the axial injection method is more advantageous than the commonly used radial injection method. This is because the axial injection promotes radial temperature gradients, with warm gas at the centre where it is isolated from the cold tank wall. Radial injection on the other hand promotes axial temperature gradients, where warm gas at the top is in direct contact with the tank wall and top tank bulkhead.

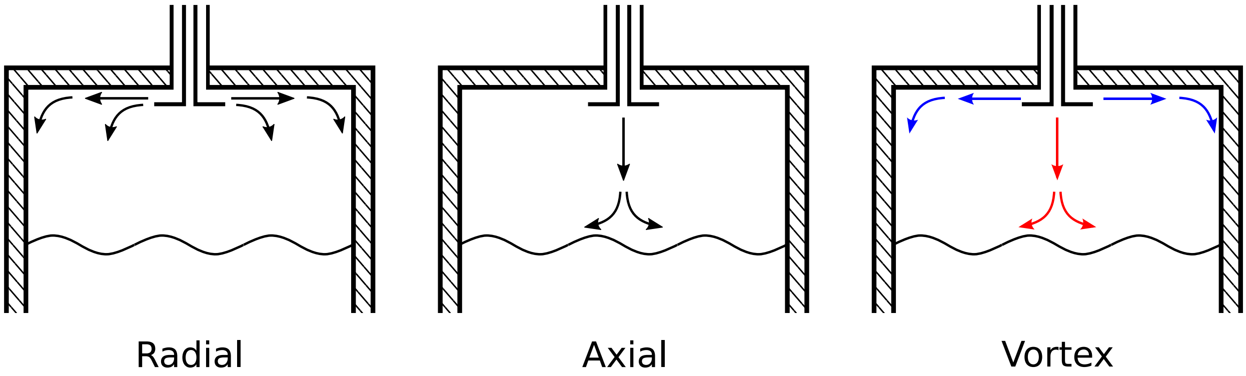

Figure 1: Three different methods of pressurant gas injection. Radial injection on the left, axial injection in the middle, and vortex injection on the right.

Based on the analysis by DeWitt et al. regarding the temperature gradients, and inspired by a small “note-in-passing” in the book of Huzel,[8] a third possible method of injection was thought of for this thesis. This involves a so called Ranque-Hilsch-vortex-tube. A vortex tube is a simple and light mechanical construction without moving parts that splits an incoming gas flow into a cold and a warm gas stream.[7] Huzel suggests to use this system to protect cold cryogenic tank structural members from the incoming hot pressurant gas. The idea considered for this project however is to use a vortex tube specifically to introduce a large radial temperature gradient in the pressurant ullage. This is expected to provide an even higher temperature gradient than axial injection, and thus an even lower heat loss to the tank wall. The way the gas is proposed to be injected after it is split into a hot and cold stream by the vortex tube is shown on the right in figure 1. The warm stream is injected axially while the cold stream is injected radially. (The vortex tube itself is not shown in the schematic.)

4. Simulation efforts

To gain insight into the thermodynamic effects of the pressurization and pressurized expulsion, and in an attempt to try and predict the collapse factor, a computer model of the system has been developed. The model was developed in Python, using the CoolProp library[2] for all fluid properties. Initially a lumped parameter model has been developed that consists of eight different nodes representing various fluid sections or tank wall sections within the system. The model is schematically shown in figure 2. Between the nodes the model calculates energy and mass flow in each time step.

The boundary between the two tank wall sections shifts along with the propellant liquid level and is modelled as a mass and energy ‘flow’ between the two wall sections flowing from bottom to top as the tank empties. Conduction is modelled by Newtons law of heat transfer. For the convective heat transfer the model uses standard Nusselt number correlations from White[11] and Bejan.[1] Mass transfer was based on standard correlations from White.[11] Heat exchange with the environment is neglected. The tank walls and bulkheads of the propellant tank are modelled using relations for heat capacity and heat conductivity for aluminium as a function of temperature.[3,13] The pressure regulator is modelled as a chocked orifice where the term $C_D A$ (discharge coefficient times orifice cross-sectional area) is modelled as a function of P_{pres} (pressurant tank pressure) and ΔP (the difference between regulator set pressure and actual ullage

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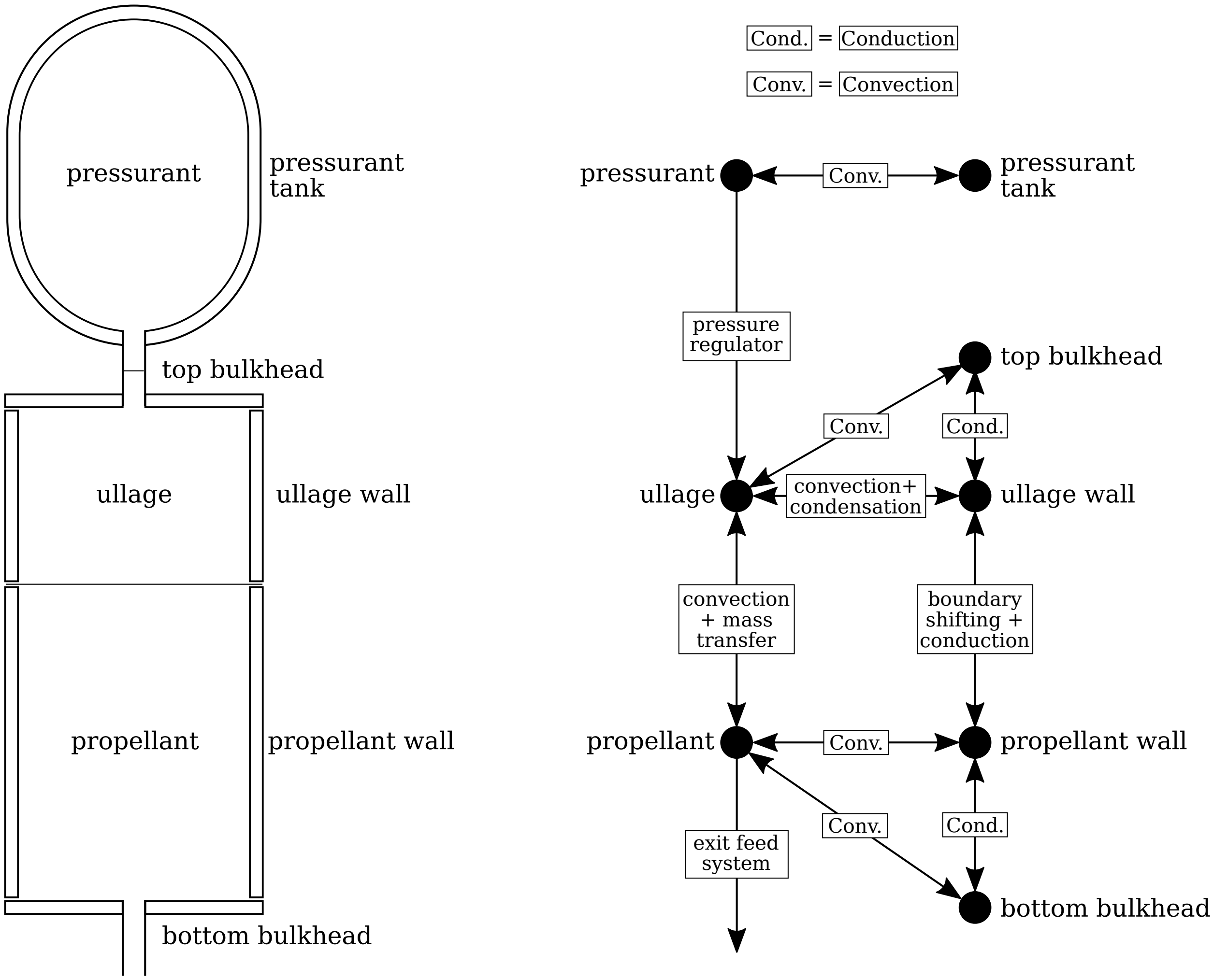

Figure 2: A schematic representation of the lumped parameter model of the tank pressurization system. The nodes and the ways they interact are shown on the right.

pressure). This function was determined by interpolation from values of the datasheets available for the regulator used during the tests.

The lumped parameter model has been further developed into two forms of a 1D simulation. Here the tank wall is split into a large number of small identical wall sections instead of the two sections used in the lumped parameter approach. The ullage gas volume is split into either multiple horizontal 'slices' or into multiple concentric cylinders. The first form (horizontal slices) is the common approach to model tank pressurization systems. It allows for the existence of vertical temperature gradients, and is thus suited to model radial injection. The second form was attempted to see if concentric cylindrical sections spanning the full height of the ullage section are better suited to model radial temperature gradients, and thus axial injection.

During the development of the code it was realized that the problem of modelling the heat transfer is more difficult then expected beforehand. The situation in the tank, with low gas injection velocity, very high temperature differences, and high pressures and densities produces a situation where it is not clear whether natural or forced convection plays the dominant role. It was chosen for the development of this model to implement only the natural convection as this will also be applicable during the pressurization phase, when little gas is injected. However, even for only this, there are no Nusselt number correlations found that are directly applicable to the situation in the tank.

From analysis it also became clear that the method of gas injection, and the resulting flow pattern of gas in the ullage volume, either strengthens or weakens the pattern of natural convection that already occurs in the tank. This is shown schematically in figure 3. The tank wall and propellant are near -196°C while the injected gas is near room temperature. This means that the natural convection pattern in the tank will have gas cooling and flowing down at the tank wall. Radial injection produces the same flow pattern as natural convection, thus strengthening the total heat transfer. Axial injection causes a flow pattern that is exactly opposite to the natural convection pattern, and thus

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weakens it. This is in line with the conjecture that axial injection produces a lower collapse factor than radial injection for this case of tank pressurization.

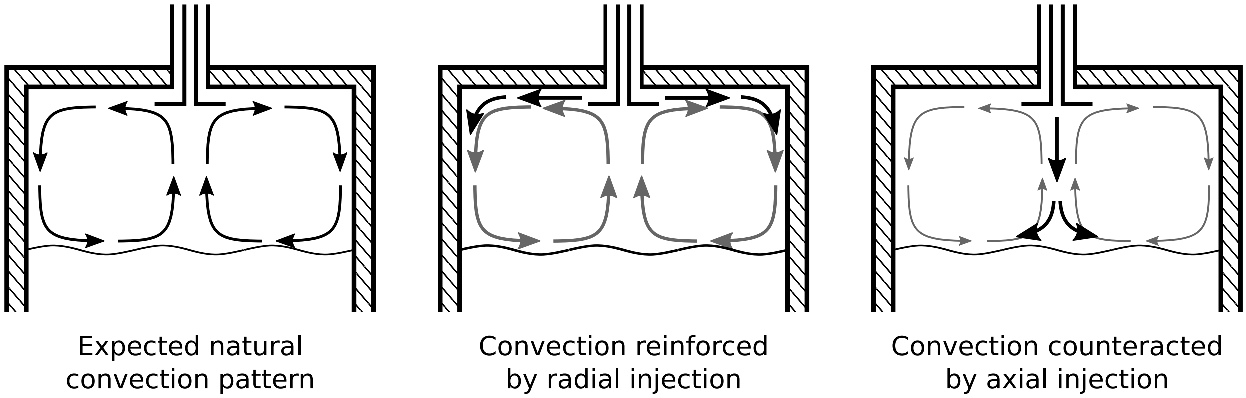

Figure 3: Radial and axial injection flow patterns in comparison to the natural convection present in the tank ullage.

The different modelling methods have been subjected to various verification tests and a sensitivity analysis. It was found that mass transfer between the ullage and propellant to play a marginal role in the total process, not influencing the collapse factor prediction by more than 1 or 2 percent. This mass transfer included condensation and evaporation of liquid oxygen, but not the possible dissolving of helium into the liquid oxygen. The influence of heat transfer could be as large as 10% to 15% on the collapse factor as it is estimated that heat transfer coefficients might differ up to a factor 2 due to the previously described difficulty in estimating these coefficients.

The models have also been compared amongst each other. In general all models (lumped parameter, 1D horizontal slices, and 1D vertical cylinders) predicted similar values for average tank pressure and total expulsion time of the propellant. Results for simulations modelling the physical test setup (section 5) were within 5% from each other. With respect to the collapse factor, and thus the total helium gas mass required, the results did differ more. The 1D horizontal slices model predicted a collapse factor 10% lower than the lumped parameter model. The 1D vertical cylinders model predicted a collapse factor 25% lower than the lumped parameter model. In general all models under-predicted the collapse factors found in the tests, as is discussed in more detail in section 7.

The difference in predicted collapse factor between the two different versions of the 1D model does indicate that a ullage volume with a predominantly radial temperature gradient will have a lower collapse factor than a ullage volume that has a predominantly vertical temperature gradient. These types of gradients are expected to be associated with an axial injection and a radial injection of pressurant gas respectively. The simulation thus also suggests that axial injection will result in a lower collapse factor, however for both cases it is expected that mixing in the ullage volume can be a significant factor for the temperature distribution.

5. Test setup

A hardware test setup has been constructed for the conduction of pressurization and expulsion tests. This has been done to collect measurement data on tank pressurization and pressurized expulsion, to validate the simulation models, and to gain experience with high pressure cryogenic systems in general. Tests have been conducted using liquid nitrogen instead of liquid oxygen to avoid the hazards resulting from the reactive nature of the latter.

The setup consists of an insulated aluminium tank with an attached feed system, suspended in an aluminium test bench. The test setup is shown in figure 5.

The feed system layout is shown in figure 5. The main piece is the insulated aluminium tank. It is constructed out of a 10 mm thick cylindrical aluminium wall with an outer diameter of 250 mm. The ends are sealed with two flat aluminium bulkheads of 30 mm thickness. All parts are of aluminium 6082-T6. The bulkheads are fixed into the tube by radial stainless steel bolts. The dimensions of the inner volume of the tank are 740 mm length and 230 mm diameter, giving a total volume of approximately 30.7 L. The main valve is a 3/4” stainless steel valve. The exit orifice is a square edged orifice, 3.8 mm in diameter. Helium is supplied directly from a standard 50 L, 200 bar gas cylinder.

The tank is equipped with a variety of sensors. The tank is suspended in the aluminium frame on two flexible plates. A load cell is used to measure the mass of the tank (and thus the mass and mass flow of liquid nitrogen). Two pressure sensors are used to measure tank pressure and pressure drop across the injector**. A total of 16 thermocouples

**No measurable pressure drop was found during the tests.

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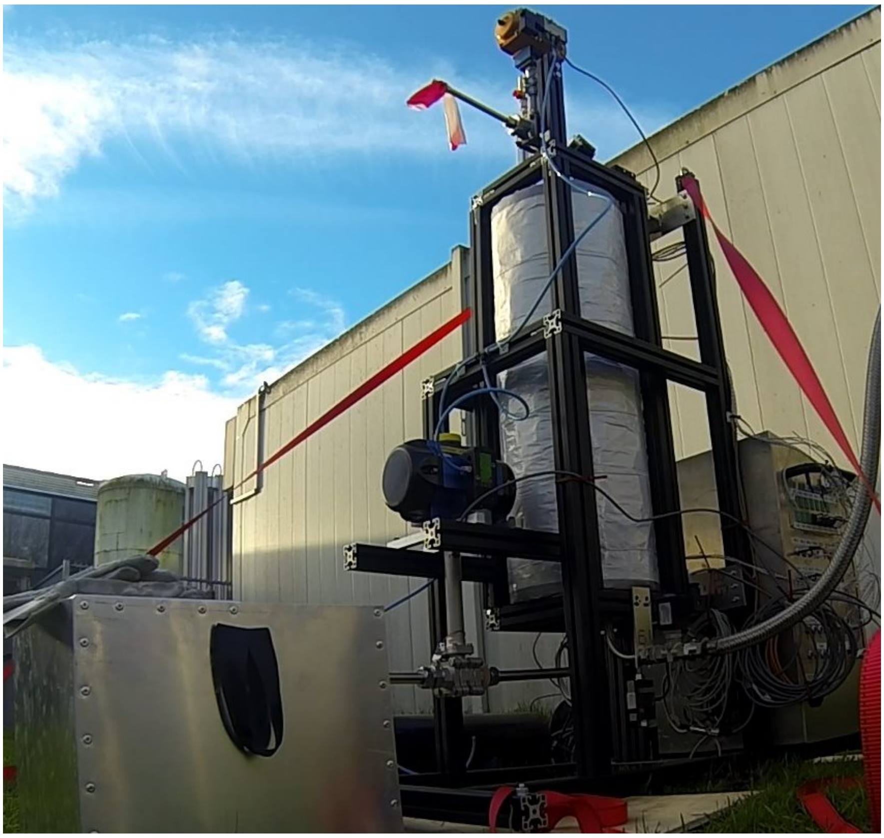

Figure 4: The test setup used during tests. The tank covered in white isolation material is visible, suspended in the black aluminium frame. The measurement and actuation system is visible at the back. The pneumatically actuated bleed valve (yellow, at the top) and main valve (blue, at the bottom) are visible. The supply dewar with liquid N_2 was placed to the right. The aluminium box in front left was used to catch the N_2 blown from the tank.

are placed in and on the tank. One thermocouple (K-type) is placed in the helium feed line to measure temperature of the inflowing helium gas. The remaining 15 thermocouples (T-type) are placed on 3 vertical lines. On each line are 5 thermocouples spaced at 100 mm intervals, starting 100 mm below the bottom of the top bulkhead. The first line is placed in the tank at 35 mm from the tank axis. The second line is placed in the tank at 95 mm from the tank axis. The third line is placed on the outside tank wall. See also figure 8 for an illustration of the thermocouple positioning.

The sensor data is recorded, and the feed system is actuated via a remote controlled system using a National Instruments cRIO system and a custom made LabView program.

An experimental capacitive liquid level sensor was used in an attempt to measure liquid level in the tank directly. The sensor used a metal rod (1.5 mm diameter) placed concentrically inside a metal cylinder (8 mm outer, 6 mm inner diameter), spaced by means of PTFE strips. The capacitance between these two elements was measured using a Texas Instruments FDC1004 chip. The measurement results showed a very good correlation between the capacitive sensor output and the measured tank mass during pressurization and expulsion of the liquid nitrogen. It gives a signal with less noise than the load cell allowing for a better insight in the exact mass flow versus time. Unfortunately however the sensor showed a slight temperature dependency which means its measurement results can only be interpreted by calibration with respect to the load cell in post-processing. The temperature dependency is expected to be due to the presence of the PTFE strips which might show changing dielectric properties with temperature.

A vortex tube was constructed in metal to be used with high pressure helium. Various tests using pressurized air and pressurized helium at a number of configurations were conducted to investigate and characterize the vortex tube. For more details on these tests please refer to the full thesis report.[6]

6. Measurement results

A total of 7 injection tests have been conducted using the test setup. Of these tests, three used the radial injection method, three used the axial injection method, and one used the vortex tube injection method. The vortex tube test

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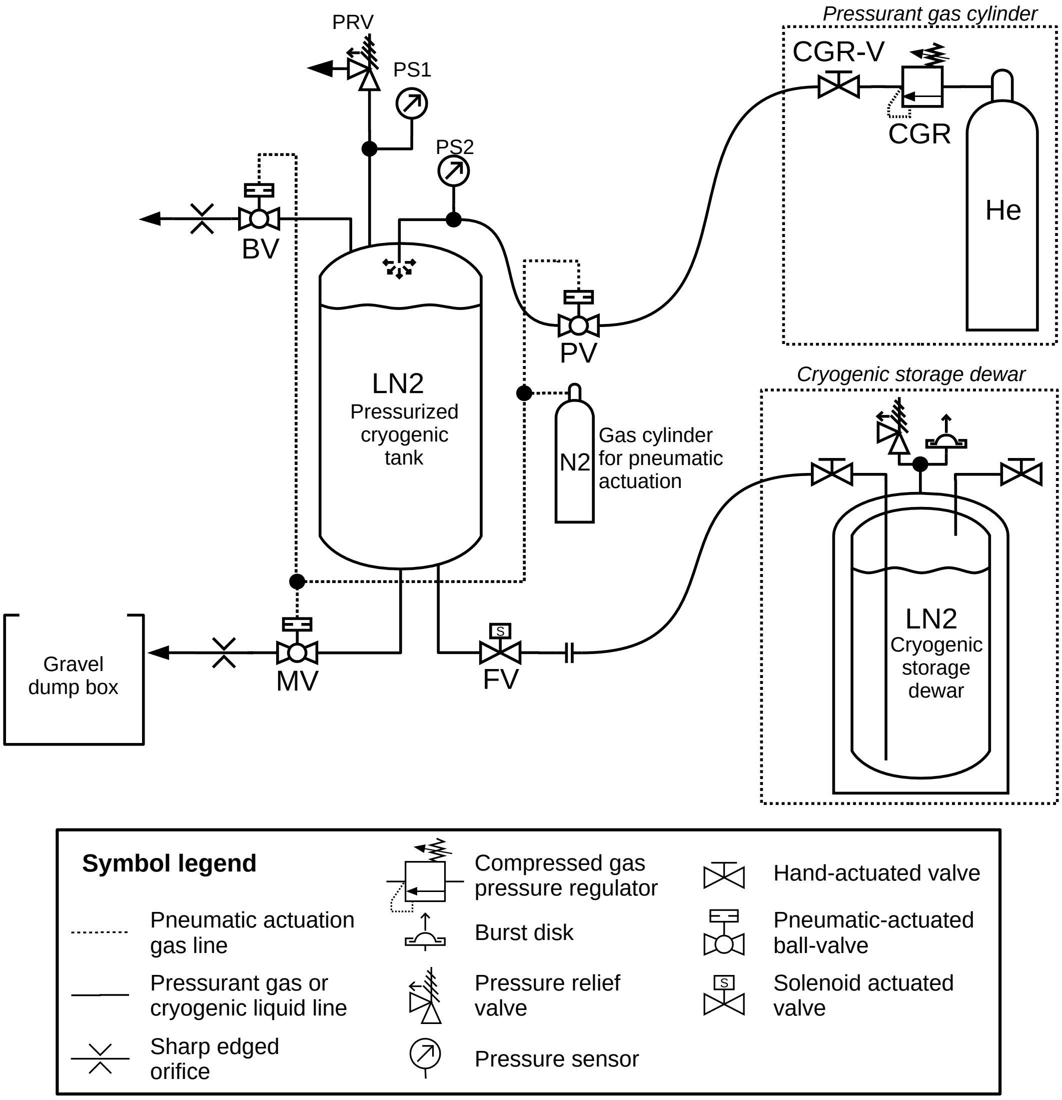

Figure 5: Feed system schematics of the test setup used during the validation tests.

is however not considered valid as a small metal sliver blocked the exit orifice, limiting the mass flow out of the tank significantly. This made the test unsuited for direct comparison to the other tests. The radial and axial injection tests were conducted on two consecutive days. Tests were conducted outside, in equal weather conditions. The radial tests are designated 'rad1', 'rad2' and 'rad3' respectively and likewise the axial tests are designated 'ax1', 'ax2' and 'ax3' respectively.

All tests were conducted by first filling the tank with liquid nitrogen at atmospheric pressure till it had reached a fill level of approximately 85%. On average the fill level was 83.2%, ranging between 80.5% and 86.4%. When the tank was filled sufficiently, the fill valve (FV) and bleed valve (BV) were closed. (See figure 5 for the position of the valves and the abbreviations.) Pressurization started by opening the pressurization valve (PV) at t = 0 s. The pressure regulator was set to approximately 30 bar each time. Pressurization lasted for 60 s, after which the main valve (MV) was opened for 50 s. During these 50 s expulsion of the nitrogen took place, draining the tank nearly fully each time. At t = 110 s MV and PV were closed and BV opened to de-pressurize the system. The whole process was executed automatically by the control software. The amount of helium gas used was determined by measuring the cylinder pressure before and after the test, allowing for enough time after each test to let the gas return to thermal equilibrium with the environment.

Pressure profiles for each test appeared as those shown in figure 6. At t = 0 s the tank pressure rises sharply, levelling off to reach its maximum near the end of the pressurization phase. At t = 60 s the tank pressure experiences a sharp drop when the liquid nitrogen flow starts. This indicates that the pressure regulator is actually slightly undersized for the desired flow rate and pressure.

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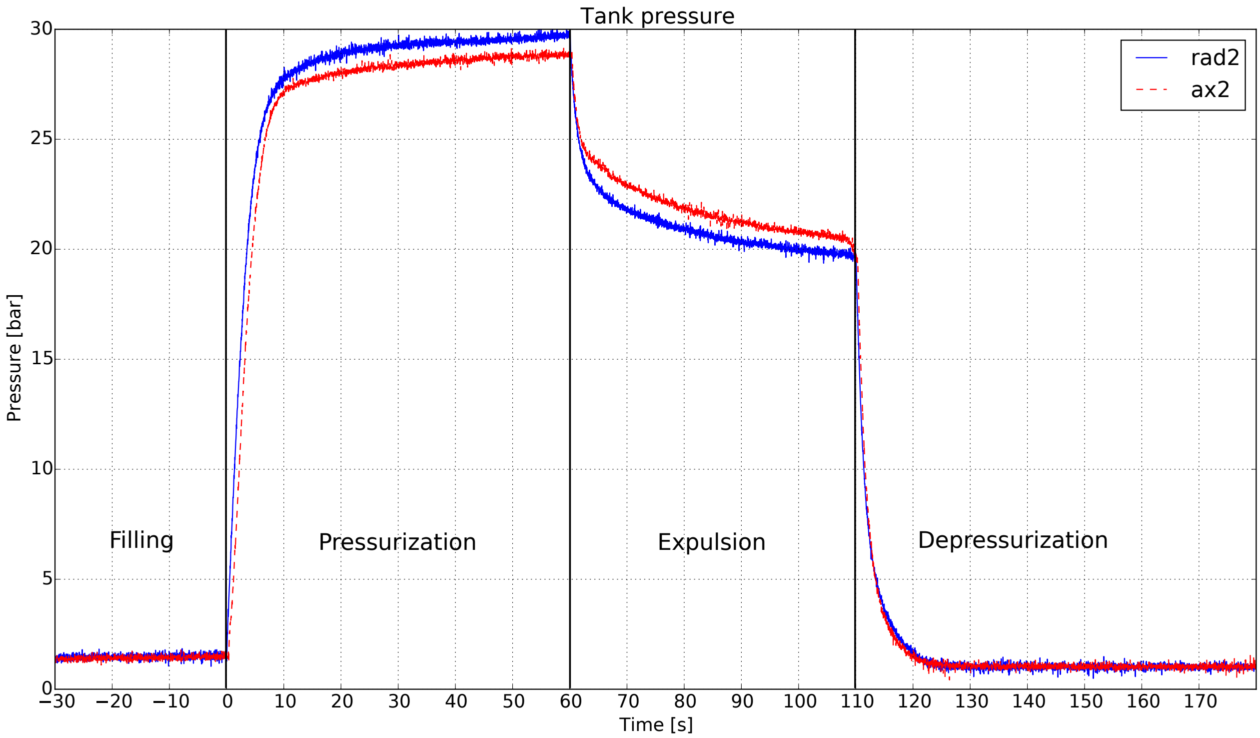

Figure 6: Typical pressure versus time curves as measured for the tests. These are for the second radial injection test and the second axial injection test respectively. The different phases in the test are indicated.

The mass flow of liquid nitrogen observed was on average 391 g/s for each test. The values ranged between 371 g/s and 402 g/s.

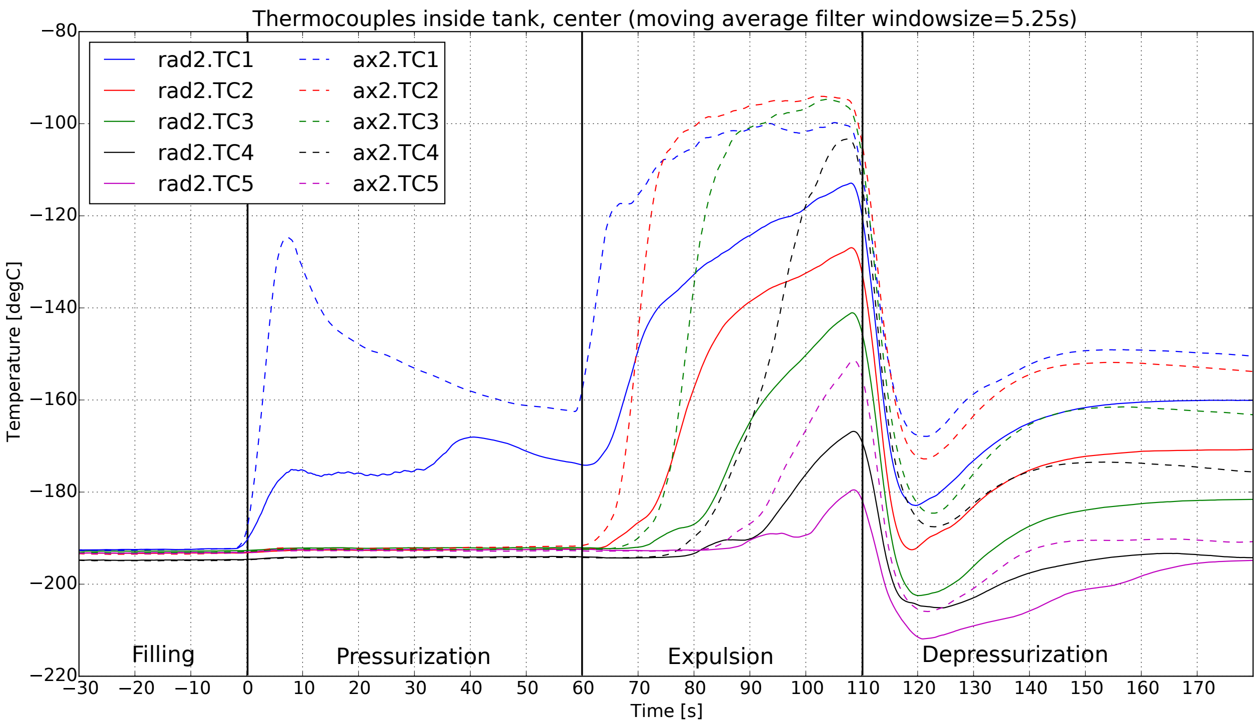

Figure 7: Temperature histories from 5 thermocouples during both the second radial injection test and the second axial injection test. A moving average filter of width 5.25 s has been applied over all curves.

Figure 7 shows temperature measurements of five thermocouples versus time for the second radial injection

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test and the second axial injection test. The five thermocouples are those near the tank centreline (35 mm from tank axis). The thermocouples are labelled TC1 through TC5, with TC1 being 100 mm below the inner surface of the top bulkhead, and each subsequent thermocouple 100 mm lower. The shapes of the curves over time and the absolute temperatures at each position vary distinctively. The temperatures from the axial test all show a very quick increase in temperature as soon as the nitrogen level drops below them. They all rise quickly to values around -100 °C and remain reasonably stable around there. Even TC4, which is just under the middle of the tank, reaches this 'warm' level just before de-pressurization. This shows that there is relatively little vertical temperature gradient within the tank. On the other hand, all thermocouples in the radial test show different behaviour: first a short rise, followed by a slow increase. The values also do not reach a common plateau, instead they show a strong vertical temperature gradient, between 1 to 2 K/cm. Overall the temperatures for the radial injection fall very much short of those achieved during axial injection.

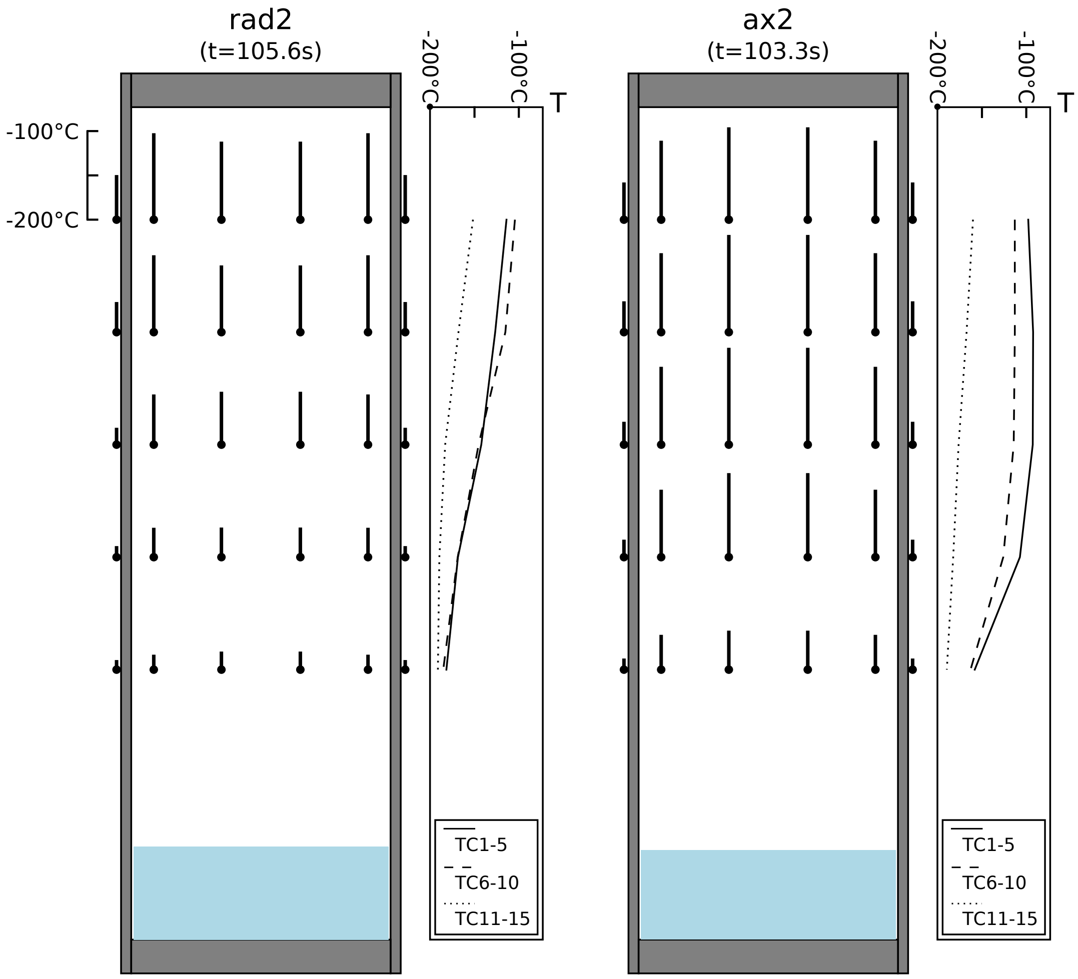

Figure 8: A representation of the test tank cross-section, the thermocouple positions, and the temperatures measured by them. The thermocouples and their measurements are mirrored over the tank axis to better show the radial temperature distribution. The blue area at the bottom of the tank indicates the liquid level of nitrogen at that point. All dimensions, positions and temperature plots are to scale.

The difference in temperature distributions is more clearly visualized in figure 8. Here a cross-section of the tank is shown for both the second radial test (left) and the second axial test (right). The images and the positions of the thermocouples are to scale. The thermocouples have been mirrored across the tank centreline to better illustrate the temperature distribution. The temperatures measured at the indicated points in time are represented by scaled black bars. These illustrate the differences between the radial and axial injection methods. With radial injection the radial temperature distributions shows high temperatures near the tank wall, and colder temperatures near the tank axis. The axial test shows the opposite: colder near the tank wall, and warmer near the tank axis. With radial injection the warmer temperatures of the gas near the wall will result in a larger heat transfer from the gas towards the wall.

In both cases the radial pattern does weaken further towards the bottom of the tank. The vertical temperature distribution, shown by the curves to the right of each tank, however show that the vertical temperature gradient is far

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more pronounced with radial than with axial injection. With radial injection the temperature drops nearly linearly with height, cooler near the bottom, warmer near the top. With axial injection the temperature however remains relatively steady over the top half of the tank, only dropping near the bottom. Overall this means that the gas in the tank is warmer during axial injection. This means that the energy content of the gas is higher with axial injection. As the injected gas is of equal temperature and pressure for both tests this means with axial injection less energy is lost from the gas towards the cold tank wall and propellant.

Table 1 lists the most important parameters of both the second radial test (rad2) and the second axial test (ax2) and the relative difference between them. All parameters concerning liquid nitrogen mass, and most concerning pressure history match up quite nicely. Test ax2 saw a slightly higher pressure, along with a longer fall time during expulsion. The collapse factor and pressurant masses are however the most interesting values. The collapse factor for the axial test is 17.6% lower than that for the radial test. Similarly, the pressurant gas mass used is 20% lower. This is a result that is in line with the main hypothesis that was to be tested: the axial injection method is more effective than the radial one. The remaining parameters strengthen the result, as the average pressure and the final pressure for the axial test are actually higher than those of the radial one. Increased pressure means increased density in the gas, which in turn increases heat transfer and thus higher collapse factor. However still the value for axial injection is lower.

An overview of test results for the other tests is given in the next section in table 2. It can be seen that the tests match up quite well in parameters showing the repeatability of the tests.

The collapse factor has been calculated using equations 1, 2 and 3. For the pressure term in equation 1, the average pressure measured during expulsion was used. For the volume the initial propellant volume in the tank was used. On average, for all three radial injection tests, the collapse factor was measured to be 2.70. For all three axial injection tests the average collapse factor was 2.28. This is a reduction of 16%. These results are in line with those presented by DeWitt et al.[5] and show that for small-scale, high-pressure cryogenic tanks the axial injection method is more effective than radial injection.

Table 1: Overview of all important measured parameters of the tests rad2 and ax2 and the percentile difference between the two values.

Test		**rad2**	**ax2**	**Difference [%]** *(=(ax-rad)/rad)*
Collapse factor	[-]	2.72	2.24	−17.6
Pressurant mass used	[g]	282	229	−18.8
Pressurant pressure start	[bar]	148	178	20.3
Pressurant pressure end	[bar]	112	148	32.1
Pressurant temperature	[K]	274.9	272.3	−0.9
Propellant start mass	[kg]	20.76	20.01	−3.6
Liquid level (start)	[%]	84.3	81.3	
Mass flow	[$\mathrm{kg\,s^{-1}}$]	0.395	0.402	1.8
Liquid level rate of change	[$\mathrm{mm\,s^{-1}}$]	−11.9	−12.1	
Final mass	[kg]	1.00	0.00	
Liquid level (final)	[%]	4.1	0	
Start pressure	[bar]	1.47	1.42	−3.4
Maximum pressure	[bar]	29.74	28.87	−2.9
Average pressure (expulsion)	[bar]	21.09	21.98	4.2
Final pressure (expulsion)	[bar]	19.72	20.28	2.8

7. Comparison between simulation and tests

Using the measurement results obtained from the tests it is possible to look back at the simulations (section 4). All six tests are compared to respective simulation results based on five system performance parameters. The simulation used here is the lumped parameter model, including heat transfer, but not including mass transfer. Only the results of this comparison are presented here. The simulation results from the 1D model using vertical slices are very comparable to the lumped parameter model. The results from the 1D model using concentric cylinders under predicted the collapse factor even more than the lumped parameter model did and is in general less accurate in modelling the various system parameters than the lumped parameter model.

Table 2 gives the measurement results for the five performance parameters for all six tests. For each test a simulation run with the lumped parameter model has been done, and the results of this simulation are also presented in the table. The percentile difference between the test and simulation is calculated.

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The results in table 2 show that the predictive power of the simulation is quite decent when it comes to the fluid flows within the system. The propellant mass flow is slightly under-predicted for all simulations, between 2% and 4% too low. The average tank pressure on the other hand is slightly over-predicted, with values 7% to 9% too high for the radial tests, and 3% to 6% too high for the axial tests. The combination of too high a pressure, but still too low a mass flow can mean that the density of the fluid is over-predicted by the simulation, or that the discharge coefficient for the orifice is estimated too low.

The prediction of the pressurant tank pressure at the end of the process is quite good. All values, except that for test ax1 are within 10%. They also all over-estimate the pressure. Note that the pressures listed here for the simulations are for when the gas in the bottle has warmed up again to environment after the expulsion process.

The predictions of the collapse factor and the total inflowing gas mass are unfortunately not very accurate, at least not for the radial injection tests. In general the values are significantly under-predicted. For the radial injection the collapse factor is predicted between 22% and 26% too low. For the axial tests however it is only 15%, 6% and 4% too low. For these tests the prediction is thus far better. The lumped parameter model does not make any distinction between the injection methods however. The two versions of the 1D simulation do, but these under-predict all collapse factors even further for all tests. This, as well as the under-prediction by the lumped parameter model, is suspected to be due to an under-estimation of the heat transfer rate.

Table 2: Comparison of the main performance parameters as observed during all radial and axial injection tests, and as simulated with the lumped parameter model (see section 4). The deviations in percent are calculated as the difference between simulation and test, divided by the test value (=(s-t)/t).

		Collapse factor [-]	Propellant mass flow [g/s]	Avg. tank pressure [bar]	Inflowing gas mass [g]	Pres. pressure (end) [bar]
rad1	Test	2.65	393	21.4	280	148
	Sim.	1.97	387	22.9	205	158
	(s-t)/t [%]	-26%	-2%	7%	-27%	7%
rad2	Test	2.72	395	21.1	282	112
	Sim.	2.02	386	22.7	210	121
	(s-t)/t [%]	-26%	-2%	8%	-26%	8%
rad3	Test	2.73	382	19.9	260	80
	Sim.	2.13	376	21.6	208	86
	(s-t)/t [%]	-22%	-2%	9%	-20%	8%
ax1	Test	2.37	371	19.0	236	52
	Sim.	2.01	361	20.1	178	58
	(s-t)/t [%]	-15%	-3%	6%	-25%	11%
ax2	Test	2.24	402	22.0	229	148
	Sim.	2.11	384	22.6	216	148
	(s-t)/t [%]	-6%	-4%	3%	-6%	0%
ax3	Test	2.23	401	22.0	232	109
	Sim.	2.13	384	22.6	197	114
	(s-t)/t [%]	-4%	-4%	3%	-15%	4%

8. Conclusions and recommendations

The collapse factor for tank pressurization systems for cryogenic pressure-fed rocket tanks has been investigated by means of numerical simulation and hardware tests. Next to the attempts to predict the collapse factor by simulation, it was investigated which type of gas injection would result in a lower collapse factor. It was hypothesized and subsequently proven that axial injection will result in a lower collapse factor than radial injection.

Three types of simulation have been developed: a lumped parameter model, a model where the ullage is split into vertical slices, and a model where the ullage is split in vertical concentric cylinders. Mass transfer between the cryogenic liquid and the helium was found not to be relevant for the outcome of the simulation. The lumped parameter model predicted the highest tank collapse factor, followed by the 1D vertical model. The 1D concentric cylinders model predicted tank collapse factors in the order of 25% less than the lumped parameter model.

It was discovered that modelling the heat transfer is more difficult than expected because the extreme conditions in the tank do not match with any standard heat transfer correlations. From the analysis it however became clear that an

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explanation for a difference in heat transfer between axial and radial injection can be sought in the way they counteract, respectively reinforce, the natural convection pattern in the tank ullage. The main recommendation resulting from this research is to investigate the heat transfer mechanisms and convection patterns in the tank ullage in more detail, possibly by CFD methods.

A hardware test setup has been constructed that consists of a well instrumented cryogenic propellant tank of 230 mm inner diameter and 740 mm inner length (30.7 L inner volume). During each test the tank was filled with liquid nitrogen up to a fill level of approximately 85% and pressurized to just under 30 bar with helium. The liquid nitrogen was expelled from the tank at an average pressure of around 22.5 bar. A total of six tests were conducted, three using radial injection, three using axial injection, and one using vortex tube injection. The vortex tube test was unfortunately unsuccessful.

Comparison of the test data from the axial and radial injection tests showed that mass flow and pressure versus time are similar for all tests. The temperature profiles however differ greatly. For axial injection the thermocouples in the tank registered higher average temperatures over the full duration of the test. The radial injection tests show slower rise and lower maximum temperatures. The distribution of temperature within the tank shows that for radial injection the ullage gas is warmer near the tank wall than near the tank centre. For axial injection this situation is reversed: warmer gas is near the centre and colder gas near the wall. This results in a lower heat transfer from the ullage gas to the tank wall for axial injection. Next to this difference in radial gradient, the radial injection tests also show a nearly constant vertical temperature gradient with warm gas near the top and cold gas at the bottom. This vertical gradient is virtually absent with axial injection.

Comparison between the injection tests and the simulations shows that in general the simulations under-predict the collapse factor, which is likely to be attributed to an under-estimation of the heat transfer coefficients. The pressure and mass histories can however be very well predicted by all models. Overall the lumped parameter model is able to predict the tank collapse factor for small-scale, high-pressure tanks using axial gas injection in the order of 10% accuracy. It is an improvement over the estimations for collapse factor obtainable by literature, but more investigation on the heat transfer is needed to make the model more reliable.

For more detailed information and measurement results concerning the research, the reader is referred to the full thesis report (reference[6]) that will be made available through the TU Delft online repository in mid-2017.

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