1 Introduction

Propellant sloshing in launch vehicle tanks has been an important field of research in astronautics since the beginning of the space age. The reason is quite simple. Liquid propellants make up a significant amount of the total mass of a launch vehicle. In launchers where only liquid propellant is used (for example the Delta 4, Saturn V or Falcon launch vehicles from the USA or the Russian Soyuz launcher) liquids account for about 90% of the total mass.

Also in other launchers such as the European Ariane 5 liquid propellant has a significant mass contribution. The Ariane 5 consists of two big solid propellant boosters (EAP), which make up 72% of the total lift off mass. Because the boosters contain solid propellant they are not subjected to sloshing. The main stage (EPC) and the upper stage (ESC-A) contain the liquid propellants LH2 and LOX. The mass of the liquid propellants amounts to 184.9 tons. This accounts for 24% of the total mass at takeoff, which is still a significant amount. A mass breakdown of the Ariane 5 is provided in Table 1-1. A schematic picture of Europe’s Ariane 5 launcher is depicted in Figure 1-1 (see also [1]). This picture clearly shows that most of the volume of the launcher is occupied by the liquid propellant tanks.

One can imagine that sloshing can cause significant forces on the vehicle which must be counteracted by the attitude control system. It is therefore very important to understand the sloshing phenomenon and to be able to predict the forces and frequencies introduced by sloshing liquids.

But research of liquid sloshing in containers did not begin at the start of the space age. There are many other areas were liquid motion can be of importance. For example ships transporting containers containing liquids can be subjected to forces exerted by the sloshing liquid. Also the transport of liquids by trucks is an example were sloshing motion might be of importance. However, the influence of the sloshing motion of these two examples can be limited by filling the containers as much as possible. Another example is found in the field of aeronautics. One of the earliest examples is when the wings are filled with propellant and the propellant slosh is coupled with the wing vibration modes, modifying the flutter characteristics [2]. On a larger scale, liquid motion can be of importance in large basins or harbours subjected to tidal influences [3] or earthquakes [4].

Although the above mentioned examples show that liquid slosh is of importance in many other fields, sloshing research got a boost at the start of the space age. Early research on space related sloshing dynamics has been carried out by the USA as well as in the former

Soviet Union. Arguably the best known work on sloshing dynamics is that of Abramson 1966 [5]. This work analyses different sloshing modes for containers of various geometries, as well as damping of the sloshing motion and nonlinear sloshing. Dodge 2000 [6] has revisited the work of Abramson, extending it with more accurate numerical data and knowledge obtained since the 1960s. Other well-known works are those of Miles 1984 [7], developing a weakly nonlinear theory which allows for determination of a phase diagram of sloshing motion, and Ibrahim 2005 [13], summarizing theory and fundamentals of sloshing and containing thousands of references.

	Propellant mass [tons]	**Structural mass [tons]**
2 x EAP	480	76
EPC	170	13
ESC-A	14.9	2.1
Additional structure*		21
total	664.9	112
Total lift off mass [tons]	**777**	

*contains all additional structure including payload, interstage, VEB etc.

Table 1-1. Ariane 5 ECA mass breakdown.

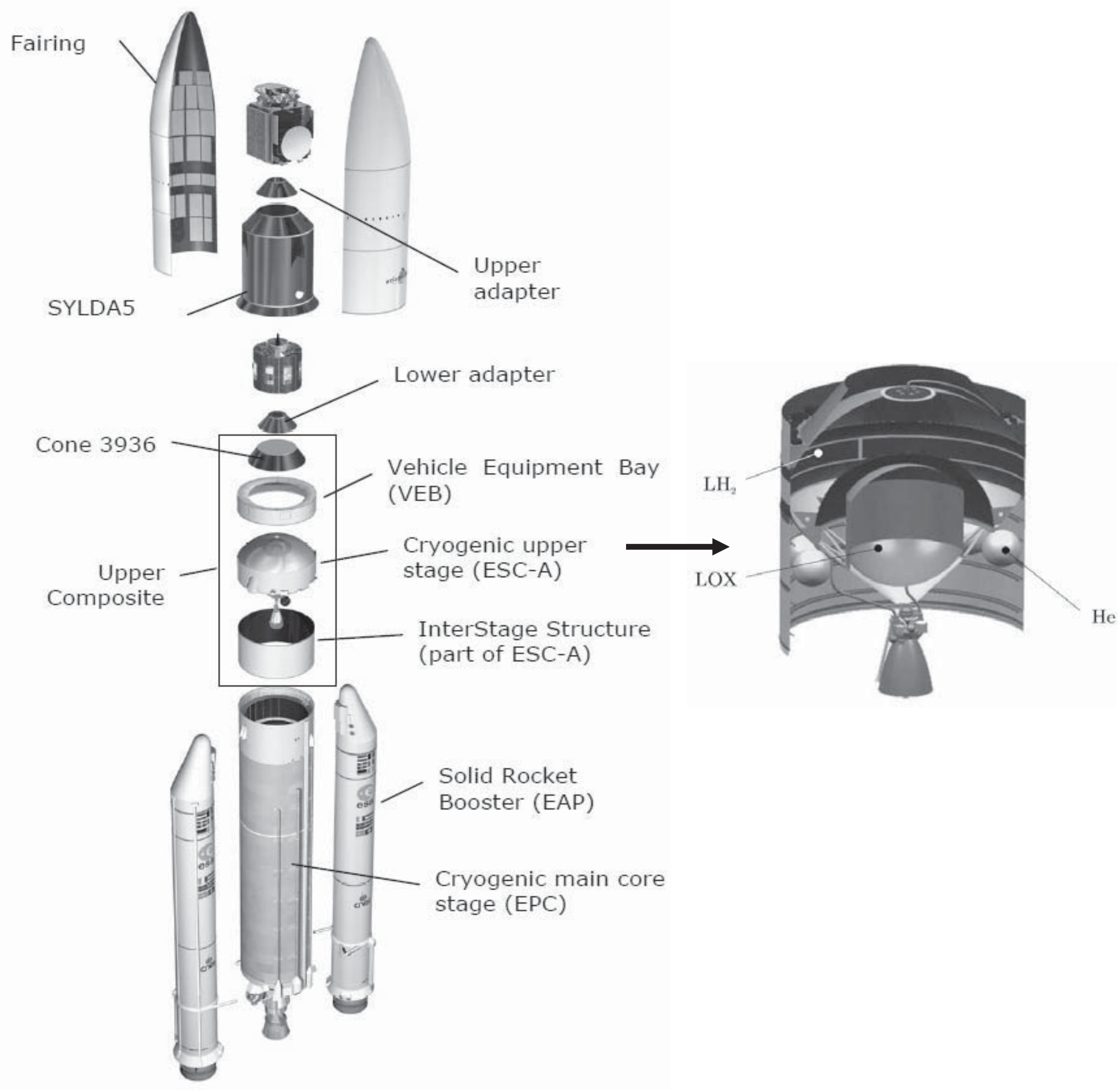

Figure 1-1. Ariane 5 ECA with ESC-A upper stage.

The dynamical behaviour of a sloshing liquid has been extensively studied. However, sloshing can lead to thermodynamic issues as well. This is especially the case when cryogenic propellants are used, such as LOX and LH2. In this case, sloshing is known to cause pressure changes in the tanks. Such pressure changes can be dangerous because launcher tanks are only structurally stable within a certain pressure range. It is therefore important to be able to predict these pressure changes. Pressure changes also have an influence on the required pressurisation gas. The ability to predict the pressure changes would also lead to a more accurate prediction of the required pressurisation gas mass.

Because of the low temperatures of the cryogenic liquid propellants, unavoidable heat leaks from the surroundings enter the propellant and propellant temperature increases. The propellant does not heat up homogeneously but instead thermal layers will form. This is referred to as *thermal stratification*. In this report it will be shown that thermal stratification is the main cause for the pressure changes observed during sloshing. This thermodynamic aspect has not been the subject of many studies. In fact, there are only three experimental campaigns which have resulted in the publication of results on this subject (excluding the experiments conducted in the framework of this PhD research). Especially in missions with long ballistic phases and greater bulk fluid motions, associated pressure changes in the system are of importance.

Currently, a new upper stage for the Ariane 5 launch vehicle is being developed in Europe. This new upper stage, which is called ESC-B (see Figure 1-2), must be able to fly longer missions with long ballistic phases and multiple engine re-ignitions. The long ballistic phases cause considerable propellant heating and the re-ignitions introduce significant sloshing. Therefore it is necessary to understand the thermodynamic aspects of sloshing better. This is why cryogenic sloshing experiments have been conducted at the Centre of Applied Space Technology and Microgravity (ZARM).

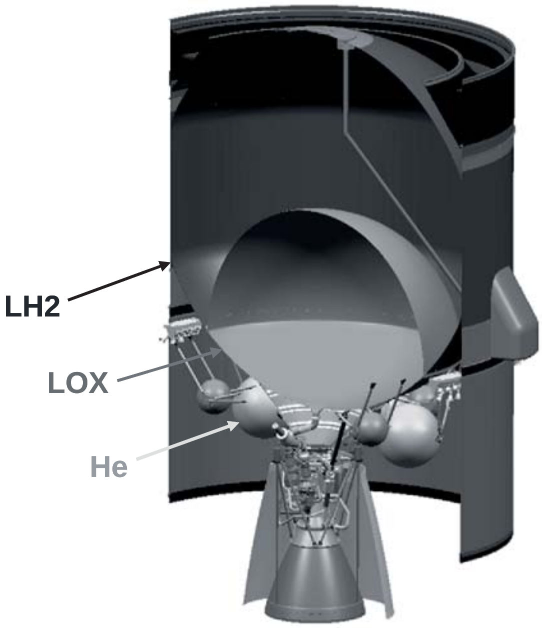

Figure 1-2. ESC-B upper stage.

1.1 State of the art

Analysis of thermal stratification in cryogenic propellants dates back to the beginning of the space age. Much literature is available on this subject, but the work of Chin et al. 1964 [21] is arguably the most commonly referenced. Ring et al. 1964 [8] present an analytical model taking into account liquid outflow. Clark 1965 [9] provides a number of references of work done on stratification available at the time. Some examples of more recent numerical studies into stratification are by Grayson et al. 2006 [10], Schallhorn et al. 2006 [11] and Oliveira et al. 2007 [12].

The influence of sloshing on tank pressure has not been the subject of many studies and is therefore poorly understood. Moran et al. 1994 [18] conducted sloshing experiments using LH2 in a spherical tank with a radius of 0.75 m. Sloshing was initiated by introducing a lateral motion to the tank. Two different excitation modes were selected, one with an amplitude of 1.5 inches (0.0381 m) and a frequency of 0.74 Hz to create chaotic sloshing, the other with an amplitude of 0.5 inches (0.0127 m) and a frequency of 0.95 Hz for stable, planar sloshing. Liquid fill height was varied, resulting in a change in eigenfrequency and resulting liquid response. Moran et al. measured pressure collapse to about 50% of the initial pressure. Results showed a clear dependency on the slosh mode (stable or unstable sloshing).

Lacapere et al. 2007 [19] conducted cryogenic sloshing experiments using LOX and LN_2 as fluids. Experiments were executed using a cryostat with a radius of 0.091 m and a height of 0.8 m. The dewar was filled to 55% of its total volume. Excitation amplitude was 0.003 m and excitation frequency was 2.1 Hz, close to the eigenfrequency of the system. This resulted in very chaotic sloshing. Lacapere et al. measured pressure collapse to about 60% of the initial pressure. Das & Hopfinger 2009 [20] conducted experiments using the liquids FC-72 and HFE 7000. Although not of cryogenic nature, the thermodynamic environment in the system was such that a pressure drop could be produced. Pressure collapse up to 57% of the initial pressure was measured. Das & Hopfinger developed an empirical model which describes pressure drop as a function of an effective diffusion constant and temperature gradient in the liquid. The experimentally determined effective diffusion constant is used as a similarity parameter to scale the experimental results to experimental data obtained by Moran et al. and Lacapere et al., with limited success.

Except for the model of Das & Hopfinger, which only describes maximum pressure drop *rates* but gives no information on total pressure drop in the system, there are no models available which can predict or simulate pressure changes due to sloshing. Much work on the understanding, prediction and simulation of pressure behaviour remains to be done.

1.2 Goal of the research and the structure of this report

The ultimate goal is to develop simple engineering models which can be used to predict the influence of sloshing on pressure. The first step is to improve the understanding of this phenomenon. Therefore sloshing experiments have been conducted using LN2. The experiments were conducted at ZARM in Bremen, Germany. The experiments were modelled using the commercially available software FLOW 3D, to create a better understanding of the physical processes involved. Once the problem is understood, the extraction of simple engineering models can be attempted. The remainder of this report is structured as follows:

- Chapter 2 presents and discusses the basic theoretical background required for this research.
- Chapter 3 describes the experimental setup and experimental results.
- Chapter 4 discusses the numerical analysis of thermal stratification and the development of an engineering model to describe thermal stratification.
- Chapter 5 elaborates on the numerical analysis of the influence of sloshing on the pressure.
- Chapter 6 provides a summary of this report.
- Chapter 7 contains the conclusions and recommendations.

2 Theoretical background & research status

This chapter provides an overview of the theoretical background applicable to the research. The focus of the chapter will lie on thermodynamics and heat transfer because experimental results are mainly explained by thermodynamic processes.
A general overview of the relevant fluid dynamics theory and equations will be given and elaborated by special cases. The special cases presented are of direct interest to this research.
The dynamics of sloshing will be discussed only briefly, as this research is not focussed on investigating dynamical features. However, to better understand the experimental results, it is important to have some basic knowledge of the dynamics. The reader is referred to [5] [6] [13] for more details on the dynamics of sloshing.

2.1 Fundamental fluid dynamics and thermodynamics equations

2.1.1 First law of thermodynamics

The first law of thermodynamics describes the change of the (internal) energy in a system due to heat added to a system and work done on this system. The first law of thermodynamics will be used in this research to determine heat input into the experimental dewar.

Energy balance for closed systems

A closed system is a system where no mass enters or exits the system. The energy balance for a closed system results in:

$$dE = dKE + dPE + dI = dQ - dW \tag{2-1}$$

where the energy E has been subdivided in kinetic energy KE, potential energy PE and internal energy I. Q represents heat entering the system and W the work done on the system.
In engineering thermodynamics the sign convention is usually as follows:

- $dQ > 0$ when heat enters the system
- $dQ < 0$ when heat leaves the system
- $dW > 0$ if work is done by the system
- $dW < 0$ if work is done on the system

This sign convention is chosen because in most thermodynamic systems encountered in engineering, the heat entering the system is transferred into work done by the system. In this nominal case values of heat and work are thus positive.

Neglecting kinetic and potential energy effects equation 2-1 can be rewritten as:

$$dQ = dI + dW = dI + pdV \qquad 2\text{-}2$$

where V is the volume. In mass specific terms this can be written as:

$$d\tilde{q} = di + dw = di + pdv \qquad 2\text{-}3$$

In appendix IV it is shown that this can also be written as:

$$d\tilde{q} = di + pdv = c_v(T, v)dT + T\left(\frac{\partial p}{\partial T}\right)_v dv \qquad 2\text{-}4$$

where c_v is the specific heat of a fluid at constant volume. For ideal gases this reduces to:

$$d\tilde{q} = di + pdv = c_v^0(T)dT + pdv \qquad 2\text{-}5$$

In some cases it is convenient to introduce the enthalpy H:

$$H = I + pV \qquad 2\text{-}6$$

In mass specific terms this can be written as:

$$h = i + pv \qquad 2\text{-}7$$

The derivative gives $dH = dI + pdV + Vdp$. Using this, equation 2-2 can be rewritten as

$$dQ = dH - Vdp \qquad 2\text{-}8$$

Or in mass specific terms:

$$d\tilde{q} = dh - vdp \qquad 2\text{-}9$$

In appendix IV it is shown that this can also be written as:

$$d\tilde{q} = dh - vdp = c_p(T, p)dT - T\left(\frac{\partial v}{\partial T}\right)_p dp \qquad 2\text{-}10$$

where c_p is the specific heat of a fluid at constant pressure. For ideal gases this reduces to:

$$d\tilde{q} = c_p^0(T)dT - vdp \qquad 2\text{-}11$$

c_p and c_v in liquids

For incompressible substances, $c_p = c_v$ and equations 2-4 and 2-10 can be written as $d\tilde{q} = c_v dT = c_p dT$. In literature it is often stated that because liquids are almost incompressible, these two values will be almost equal. This is **wrong**. Although the specific volume v shows only very little variation with temperature or pressure, this does not mean that c_p and c_v are equal. In fact, in the case of liquid nitrogen, the difference between c_p and c_v can be as large as a factor 1.9. Using the correct value of specific heat is important for the 1D engineering models (chapters 4 and 5). A discussion on the difference between the two specific heats can be found in appendix IV. The reader is urged to study this appendix carefully.

Energy balance for open, unsteady systems

In open systems mass enters and/or exits the system. Using a control volume for analysing the system under consideration the energy balance for a control volume results in:

$$\dot{E}_{cv} = \dot{KE}_{cv} + \dot{PE}_{cv} + \dot{I}_{cv} = \dot{Q} - \dot{W} + \sum_i \dot{m}_i\left(i_i + \frac{u_i^2}{2} + gz_i\right) - \sum_e \dot{m}_e\left(i_e + \frac{u_e^2}{2} + gz_e\right) \qquad 2\text{-}12$$

where the terms $\dot{m}\frac{u^2}{2}$ and $\dot{m}gz$ represent the changes to the kinetic and potential energy by the incoming and/or exiting flow. The work W in an open system consists of two parts. The first part is the work introduced at the inlets and exits where mass enters or exits the control volume and the second part is all the other work on the control volume (also referred to as technical work). This means the work can be written as $\dot{W} = p_e S_e u_e - p_i S_i u_i + \dot{W}_{cv}$, where the first two terms involve the work done by the entering and exiting mass and u_e and u_i are the exit and inlet velocities respectively. Because $Su = \dot{m} v$ (where v is the specific volume) and the specific enthalpy h is defined by $h = i + pv$, the above equation can be rewritten in terms of specific enthalpy of the entering and exiting flow:

$$\dot{E}_{cv} = \dot{KE}_{cv} + \dot{PE}_{cv} + \dot{I}_{cv} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{u_i^2}{2} + g z_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{u_e^2}{2} + g z_e \right) \qquad \text{2-13}$$

By neglecting potential and kinetic energy effects the following relation is obtained:

$$\dot{I}_{cv} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i\, h_i - \sum_e \dot{m}_e\, h_e \qquad \text{2-14}$$

2.1.2 Fundamental fluid dynamics equations

To understand convective heat transport and phase change processes better requires an understanding of the fundamental fluid dynamics equations. Three fundamental equations exist, namely the conservation of mass equation, the conservation of momentum equation and the conservation of energy equation. These are presented below under the following assumptions:

1. Single species system
2. Viscosity, heat conductivity and heat capacity are constant
3. In the energy equation kinetic effects can be neglected as well as viscous heating and heating due to body forces
4. Newtonian behaviour of fluid
5. No slip at the liquid vapour interface
6. No slip at walls
7. No temperature jumps
8. No interface resistance for phase changes
9. Temperature at free surface is equal to the saturation temperature

For each equation the applicable boundary conditions will be provided. This includes boundary conditions at a liquid vapour interface.