# Chapter 1

# Introduction

The following chapter is based on the publication Pingel and Dreyer 2019 [73].

## 1.1 Background

A cryogenic tank for spacecrafts or rockets has the function to store the liquid propellant phase as it is needed for the engine at certain mission times. In general, the liquid phase is exposed to its own gaseous phase, building a single species two phase fluid system. The mass fraction of liquid and gas inside of the tank hereby depends on the initial liquid fill level and the thermodynamic state of both phases, which can change in time. Due to incoming heat fluxes through the tank walls, a part of the liquid phase can be forced to evaporate, increasing the overall tank pressure (boil off). In order to not overcome a certain pressure maximum, a part of the gas mass inside of the cryogenic tank has to be vented through a gas outlet (gas port) at certain mission times. During this venting process, the liquid saturation temperature and pressure decrease according to the decreasing tank pressure.

While the venting process takes place, the liquid phase inside of the tank does not necessarily rest at the tank bottom (settled state). Due to acceleration changes of the spacecraft or rocket a liquid movement can occur, especially in the ballistic flight phases, where remaining gravitational forces become less dominant. As soon as the moving liquid enters the open gas outlet, a liquid outflow can establish as well as the temporal blocking of the gas port. These phenomena have been reported by Behruzi et al. (2006) [5] during the evaluation of the measured flight data of the first Ariane 5 flight with the cryogenic upper stage ESC-A. The loss of liquid propellant for the main engine and the appearance of thrust fluctuations of the cold gas thrust system caused the need of a liquid-gas phase separation at the gas port.

In order to perform passive phase separation in propellant tanks, metal screens are widely used as components for fluid handling. A screen can be understood as an open porous medium. Because the thickness of a screen normally is much smaller than the remaining geometrical dimensions, it can be treated as a quasi two dimensional porous medium. The fluid behavior inside of porous media under reduced gravity has been investigated quite well in literature, for example by Smirnov et al. (1999) [82], Smirnov et al. (2003) [84], Smirnov et al. (2003a) [83], or Schramm et al. (2003) [79]. The investigations mainly focus on the understanding of capillary forces inside of porous media used for filtration processes. The wicking of liquid nitrogen into a superheated porous structure restrained by Earth's gravity has been investigated by Grebenyuk and Dreyer (2016) [44]. In contrast to experiments with storable liquids Grebenyuk and Dreyer (2016) [44] used a cryogenic liquid in a single species two phase fluid system. The wicking of the cryogenic liquid into the superheated porous structure has given evidence about phase change phenomena, influencing the imbibition rate into the porous medium.

In case of the fluid handling inside of spacecraft or rocket propellant tanks, screens are used to perform a passive separation of the gaseous from the liquid propellant phase. This means that the liquid is able to flow through the screen, causing a flow through screen pressure drop, while the gaseous phase is blocked due to the pressure jump across a curved liquid-gas interphase at the small screen pores at the surface. As long as the flow through screen pressure drop is smaller than the bubble point pressure phase separation is enabled, and allows the provision of gas free liquid for the spacecraft or rocket engine.

Devices which provide this functionality inside of rocket or spacecraft propellant tanks are called propellant management devices (PMD). In case of cryogenic propellants and the usage of screens to enable the passive separation of the gaseous from the liquid phase, screen channel liquid acquisition devices (LAD) are developed. A LAD consists of several closed channels which join together at the top of the tank and at the bottom, directly at the liquid outlet. At each channel one site is perforated with screens in order to let the liquid propellant phase enter the channel while the gaseous phase is blocked until the bubble point pressure is reached. The liquid inside of the channel flows to the liquid outlet in order to provide gas-free propellant for the engine. Comprehensive investigations for different screens which are probably applicable for a LAD design have been performed for liquid hydrogen and other cryogenic liquids (Camarotti et al. 2019 [18]; Darr and Hartwig 2014 [31]; Hartwig et al. 2014a [46]; Hartwig et al. 2013 [45]; Hartwig et al. 2014b [47]; Hartwig et al. 2014c [48]).

In case of the phase separation at the gas port of a propellant tank however, the opposite, the separation of the liquid from the gaseous propellant phase is needed. Liquid-gas phase separation means that the gaseous phase is allowed to enter the phase separation device while the liquid phase is blocked. This can be achieved using a double screen element.

First theoretical and experimental investigations on the passive separation of the liquid from the gaseous phase using a double screen element in Earth's gravity have been performed by Conrath et al. (2013) [25]. A two species two phase fluid system has been used, consisting of liquid silicon oil SF 0.65 in ambient air environment. In the experiments, a capillary structure has been mounted between two dutch twilled weave screens with 165 warp and 800 weft wires per square inch. Related to the experiments, numerical simulations and mathematical calculations have been performed by the authors to quantify the overall fluid behavior.

A first device which performs the liquid gas phase separation at the gas port of a propellant tank has been invented by Behruzi et al. (2013) [6]. It is called gas port phase separator (GPPS) and can be mounted directly at the gas port inside of a propellant tank. The phase separation of the GPPS occurs due to a serial connection of three different phase separation mechanisms, located in each of four inlet ports: shield plates, a double screen element and a centrifugal separator with reservoir. Through each of the four inlet ports, liquid free venting can be performed. However, if one of the inlets is imbibed by the liquid phase, further liquid flow into the GPPS is blocked by the phase separation mechanisms. At the same time, the remaining dry inlet ports still enable liquid free venting.

The double screen element is an important component for the phase separation in the GPPS. It consists of two cylindrical metal screens which are fixed inside of the cylindrical section of the inlet in a certain distance to each other. A capillary structure between the screens has not been included. For the verification of the GPPS, Behruzi et al. (2013) [6] performed several tests with storable and cryogenic liquids in Earth's gravity as well as tests with a storable liquid in microgravity. The behavior of the whole GPPS system in ballistic flight phases has been investigated numerically by Behruzi et al. (2013) [6].

## 1.2 Motivation

The presented work is related to the scientific field of application oriented basic research. The application in this case was the passive separation of the liquid from the gaseous hydrogen phase at the gas port of modern spacecraft or rocket tanks using a double screen element. The presented thesis focused on the experimental and theoretical investigations of the physical processes which are related to the retention capability of a double screen element against liquid hydrogen in Earth's gravity and in microgravity with respect to applied stimuli. Hereby, the presented thesis addresses two topics which define the two objectives of this work.

At the current state of the art, the retention capability of a double screen element against liquid hydrogen has not been investigated experimentally in microgravity. However, with regard to a possible application it is mandatory to investigate the function of the double screen element for the real propellant under relevant environmental conditions. Therefore, the first objective is the development and operation of a cryogenic test facility which enables the experimental investigation of the combined physical processes, related to the retention capability of a double screen element against liquid hydrogen in Earth's gravity and in microgravity.

The second objective is the theoretical investigation of the combined, physical processes, which have been observed in their combination during the experiments. It was of special interest to identify which physical processes occur and how they occur with respect to the applied stimuli.

## 1.3 Challenges

The considered experiments using the real propellant under relevant environmental conditions are very challenging. Liquid hydrogen is a cryogenic fluid, which means that the liquid phase can only exist at very low temperatures. The saturation line is defined between the triple point and the critical point of parahydrogen. The triple point is reached at the saturation temperature of $T_{sat,tp} = 13.8\,\mathrm{K}$ and the corresponding saturation pressure of $p_{sat,tp} = 0.07\,\mathrm{bar}$. The critical point is reached at the saturation temperature of $T_{sat,crit} = 32.9\,\mathrm{K}$ and the saturation pressure of $p_{sat,tp} = 12.9\,\mathrm{bar}$, according to Lemmon et al. 2013 [72]. In general, a helium cryostat is needed to provide the low temperature environment and to store the liquid hydrogen phase (see p. 358 ff. in Wutz et al. 2000 [96]). Hereby, the cooling fluid liquid helium is consumed continuously.

Hydrogen in a single species two phase fluid system consisting of the liquid and the gaseous phase in the wet steam area is able to perform phase change processes. Due to a certain heat input into the liquid phase or due to a depressurization of the gaseous phase evaporation can occur (see p. 15 ff. in Brennen 1995 [11]). Due to the cooling or the pressurization of the gaseous phase condensation can occur. Hereby, the thermodynamic state of liquid hydrogen in gaseous hydrogen environment changes quite fast if only a small temperature or pressure gradient is present (see Bellur 2018 [8] and Li and Ma 2016 [65]). Therefore, the accurate conditioning of the thermodynamic state of the fluid during experiments is difficult.

Liquid hydrogen in combination with oxygen is an ignitable mixture, like it is used for modern cryogenic spacecraft or rocket engines. Therefore, liquid hydrogen has to be separated accurately from ambient air and ignition sources during experiments. Furthermore, all sensors and hydraulic components which are in contact with hydrogen have to be media compatible, low temperature stable and sufficiently tight against the ambient air. This is especially challenging, if not only a cryostat is needed to store the cryogenic test fluid, but also an external hydraulic system is needed to condition and actuate the test fluid.

In order to perform first, short term investigations in microgravity three different concepts are generally available and are used stepwise: first, drop tower experiments, second, parabolic flight experiments and third, sounding rocket experiments. Drop tower experiments provide the shortest time in microgravity during the free fall of the drop capsule, including the test setup. In the drop tower at the University of Bremen the free fall duration in microgravity environment is 4.7 s. Therefore, all physical effects which have to be investigated in a drop tower experiment have to occur, have to be measured and have to be recorded during 4.7 s. At the end of one drop tower experiment the test setup has to be recovered in an intact and safe state.

In addition to that, the geometry of the test setup has to be scaled highly in order to fit into the limited volume inside of a drop capsule. A controlling algorithm to automatically start the recording of experiment images, to record the sensor data and to operate switches of a hydraulic system during free fall is needed as well.

Not only the experiments but also the mathematical and numerical modeling of the physical processes related to the retention capability of a double screen element against liquid hydrogen in Earth's and in microgravity is not trivial. A combination of fluid mechanical and thermodynamical effects in Earth's gravity and microgravity is expected. Both, the overall free surface flows in the test setup including phase change phenomena and the two phase flows in the thin, porous media have to be modeled. This can lead to a scale problem because the pores of the porous medium are at least three orders of magnitude smaller than the dimensions of the test setup. Therefore, the usage of volume averaged, macroscopic approaches to model the flows in the porous media is required.

In the following the scaled test setup for the theoretical and experimental investigations in this work is presented. The expected physical process is described in microgravity (see section 1.4) and in Earth's gravity (see section 1.5). Finally, the outline of this work is presented (see section 1.6).

## 1.4 Expected physical processes in microgravity

Consider an outer glass cylinder partly filled with liquid hydrogen (l) in a gaseous hydrogen (g) environment and a sharp interface (IF) in between, like illustrated in Fig. 1.1. Inside the outer glass cylinder (a), an inner glass tube (b) is immersed coaxially into the liquid. Inside of the inner glass tube, two screens are placed perpendicular to the glass cylinder axis. The screens are made of the same material, but they are labeled as lower (LS) and upper (US) screen. At $t_0$, the initial configuration at Earth's gravity (1g) is shown before it will be exposed to microgravity conditions (0g) during free fall in a drop tower experiment (see $t_1$). The application of a pressure difference $\Delta p$ causes the liquid to move into the inner glass tube. The inner meniscus rises up (see $t_2$). If the three phase contact line (solid-liquid-gas) at the inner wall of the glass tube reaches the lower screen, radial inward wicking starts (see $t_3$). The initially unsaturated pores of the screen are imbibed by the liquid and form small menisci at the liquid-gas interfaces. The radial inward wicking process leads to the liquid imbibition of the screen, in direction of the

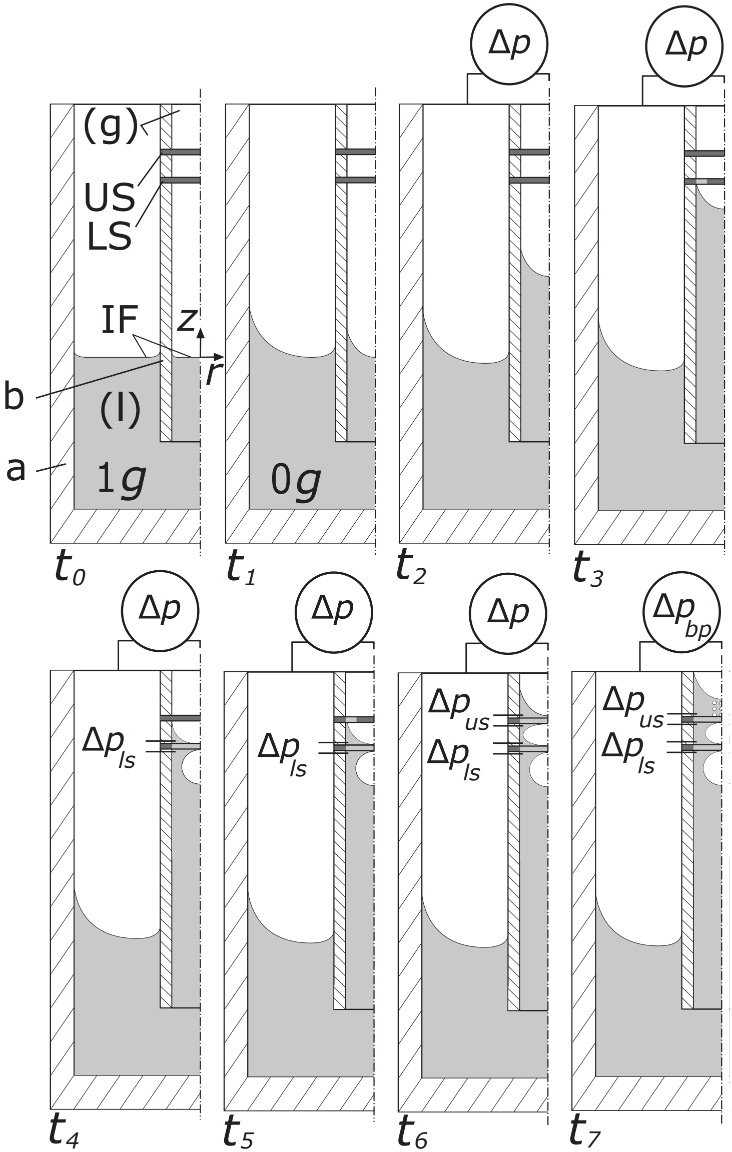


Figure 1.1: Expected physical phenomena in microgravity, according to Pingel and Dreyer 2019 [73].

screen center. At the end of the process, the initially dry screen is saturated with liquid (see $t_4$).

Dependant on the liquid rise velocity and the radial inward wicking velocity, a volume of gas can be enclosed below the lower screen after saturation. The surface of the enclosed gas volume seeks to reach a minimal surface energy and forms a spherical bubble. If the bubble touches the inner wall of the inner glass tube and the liquid is circumferentially displaced from the wall, no liquid flow can occur through the lower screen. This is very unlikely for a perfectly wetting liquid at isothermal conditions.

If a liquid path towards the lower screen persists, the applied pressure difference will cause a liquid flow through the screen. The quantity of this liquid flow is determined by the actual screen area through which the flow occurs, and the corresponding flow through screen pressure loss $\Delta p_{ls}$ (see Conrath and Dreyer 2012). This additional resistance decreases the rate at which the space between the screens is being filled with liquid. If, and when, the three phase contact line at the inner wall of the glass tube reaches the upper screen, the same radial inward wicking process takes place at $t_5$. A second gas volume can be enclosed between the screens after the complete saturation of the upper screen at $t_6$. The resulting gas bubble deforms towards a minimal surface energy as well. The shape of the bubble surface however, depends on geometrical constrictions of the double screen element. If the tube diameter is larger than the distance between the two screens, the gas volume forms an ellipsoid. If the tube diameter is smaller, the enclosed gas volume forms a spherical bubble. The enclosed gas volume is able to cover a part of the upper screen cross section. The same situation as for the lower screen may exist for the upper screen: no liquid flow occurs in case of the displacement of the liquid from the wall. Otherwise, a flow through screen pressure loss $\Delta p_{us}$ appears in case of a partly connection between the liquid below the screen and the screen itself. A second resistance is added to the flow path which either fully blocks or retards the liquid motion.

If the remaining pressure drop across the upper screen exceeds the bubble point pressure $\Delta p_{bp}$, gas is pushed through the screen. This reduces the amount of gas between the screens, which changes the effective liquid flow path and reduces the flow through screen pressure drop (see $t_7$).

## 1.5 Expected physical processes in Earth's gravity

The same setup consisting of an outer glass cylinder partly filled with liquid hydrogen (l) in gaseous hydrogen (g) environment and a sharp interface (IF) in between, is considered (see Fig. 1.2). At $t_0$, the initial configuration at Earth's gravity (1g) is shown. In contrast to the microgravity consideration (see section 1.4) the setup is exposed to Earth's gravity the whole time. The application of a pressure difference $\Delta p$ causes the liquid to move into the inner glass

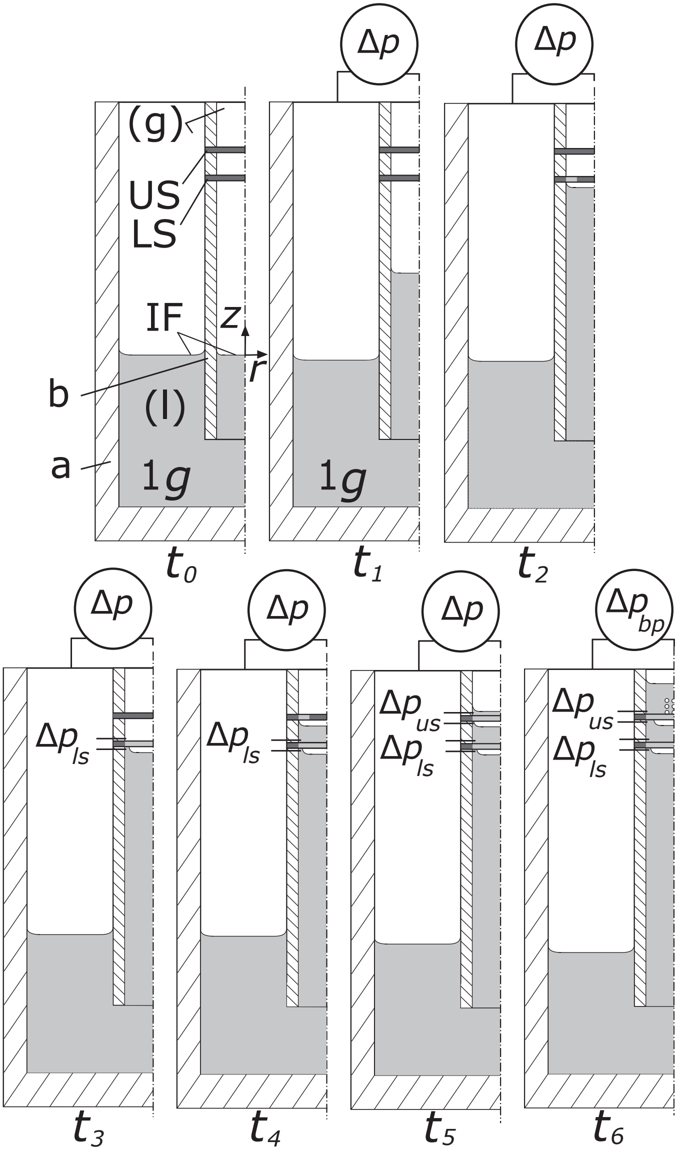


Figure 1.2: Expected physical phenomena in Earth's gravity.

tube. Hereby, the liquid movement is restrained by Earth's gravity. The inner meniscus rises up (see $t_1$). If the three phase contact line at the inner tube wall reaches the lower screen, radial inward wicking starts (see $t_2$) and ends if, and when, the screen is completely filled with liquid (see $t_3$).

Dependent on the liquid rise velocity and the radial inward wicking velocity, a volume of gas can be enclosed below the lower screen after saturation with liquid. In contrast to the microgravity consideration (see section 1.4), the surface of the enclosed gas volume is assumed to form a flat, elliptical bubble in Earth's gravity. The bubble is assumed to be smaller than in the microgravity consideration (see section 1.4). Furthermore, it is assumed that the bubble rests below the lower screen and covers a part of the cross section below the lower screen.

The same radial inward wicking process takes place at $t_4$ if, and when, the three phase contact line at the inner tube wall reaches the upper screen. A second gas volume can be enclosed between the screens after the upper screen is completely filled with liquid at $t_5$. Like for the enclosed bubble below the lower screen, it is assumed that the enclosed bubble below the upper screen is smaller than in the microgravity consideration (see section 1.4), rests below the lower screen and covers a part of the cross section below the upper screen. The following situation may exist for both screens: no liquid flow in case of the displacement of the liquid from the wall or two flow through screen pressure losses $\Delta p_{ls}$ and $\Delta p_{us}$ in case of a partly connection between the liquid below the screens and the screens itself appears. Two additional resistances are added to the flow path which either fully block or retard the liquid motion above the screens.

Like in the microgravity consideration (see section 1.4) it is assumed, that gas is pushed through the upper screen if the remaining pressure drop across the upper screen exceeds the bubble point pressure $\Delta p_{bp}$. This reduces the amount of gas between the screens, which changes the effective liquid flow path and reduces the flow through screen pressure drop (see $t_6$). In contrast to the microgravity consideration (see section 1.4) it is assumed, that buoyancy forces can have an influence on the bubble behavior.

## 1.6 Outline

This thesis comprises eleven chapters: chapter 1 includes the background, the motivation, the challenges, the expected physical processes in microgravity and in Earth's gravity and the outline of this work.

In chapter 2 the theoretical background is presented, which is based on the general accounting equations for a fluid continuum. Firstly, the general conservation equations for mass, linear momentum and internal energy are introduced. Secondly, the three heat transfer mechanisms, thermal conduction, thermal convection and radiation are presented. Thirdly, the boundary conditions and approximations are presented in order to solve the set of conservation equations. The chapter is based on relevant text book literature.

Chapter 3 includes the numerical background. This chapter presents and describes the theory and implementation of the theoretical background, explained in chapter 2, in the commercial CFD software FLOW3D version 11.2. At first, the implementation of the conservation equations for mass, linear momentum and internal energy into the VOF-method is presented. Secondly, the implementation of the solid energy conservation equation in FLOW3D follows. Thirdly, the boundary conditions and the approximation for surface tension with wall adhesion are described. Finally, the phase change model of FLOW3D is presented followed by the general solution method of FLOW3D. The chapter is mainly based on the FLOW3D users manual [38].

In chapter 4 the current state of the art is presented. The chapter comprises the explanation and quantification of the expected, governing physical processes related to the retention capability of a double screen element against liquid hydrogen. The expected, governing physical processes are: the flow through screen pressure loss, the radial wicking process, the bubble point pressure and the capillary driven liquid rise in a cylindrical tube. The quantification of these phenomena is based on mathematical relations and experimental data from the open literature. In addition to that the Joule-Thomson effect at porous media, the capillary statics of certain liquid-gas interfaces in equilibrium state, as well as evaporation and condensation at free surfaces are introduced.

In chapter 5 the numerical simulation of the expected, governing, physical processes explained in chapter 4 using FLOW3D version 11.2 is presented. Hereby, the model setups, the governing equations, the numerical results and the comparison to the results of the mathematical relations, presented in chapter 4, are described.

Chapter 6 focuses on the experimental investigations of this work. The experiment setup including the cryogenic test facility, the test cell and the measurement systems is described followed by the experimental results in microgravity and in Earth's gravity. Afterwards a comparison of the results of an experiment in Earth's gravity with a comparable experiment in microgravity is carried out followed by an analysis of the effects of the applied stimuli in the experiments. Finally a conclusion summarizes the major coming outs of the conducted experiments. This chapter is mainly based on the publication Pingel and Dreyer 2019 [73].

A mathematical model is presented in chapter 7. The model allows the prediction of the meniscus center point progression below the lower screen, between the screens and above the screens with respect to certain assumptions and simplifications. Two fitting parameters are used to approximate the movements of the meniscus center points in certain experiments. The first fitting parameter is a factor which influences the flow through screen pressure loss of the gaseous phase. The second fitting parameter is a factor which influences the flow through screen pressure loss of the liquid phase. After the fitting, the two fitting parameters have been related