Chapter 1

Introduction

Liquid flows driven by capillary forces represent an important field of research as many applications in science, industry and daily life rely on this process. For example in technical applications such as heat pipes or spacecraft Propellant Management Devices (PMDs) capillarity is of high importance. This also applies for average consumer products like marker pens, candle wicks as well as sponges. In nature capillary transport can be found in plants, where together with the osmotic pressure it facilitates the transport of water from the roots to the tips, or in the field of hydrology where the movement of groundwater is influenced by capillary transport as well. Typically, this transport occurs in complex shaped structures. However, many flow or layout calculations adopt models for cylindrical tubes or simplified porous materials to match the flow in arbitrary shaped capillaries. Despite their reduction in complexity, macroscopic approaches to capillary transport have been very successful in describing many of the presented problems.

A large amount of literature is devoted to capillary transport but there is still a need for fundamental research to fully understand the processes. Due to the described relevance for technical applications experimental data, models, and numerical simulations are of importance to engineers designing heat pipe systems or PMDs for instance. Besides these applications, capillary transport processes are also a very interesting subject for fundamental research in a sense of pure science. By analytical means theoretical modeling or dimensionless scaling can be conducted - e.g. based on the momentum balance of a fluid inside a porous structure - and then compared to experimental data for validation purposes. These processes also provide good test cases for validation of CFD tools to enable a deeper insight into the fluid mechanics behind capillary dominated problems.

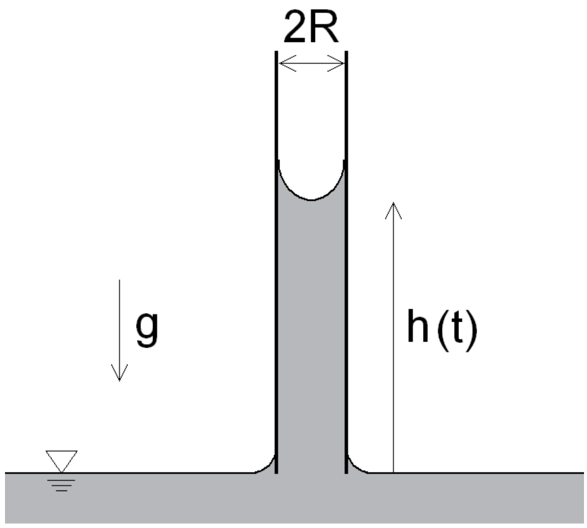

Figure 1.1: Liquid rise in a capillary tube of inner radius R. Gravity vector g is parallel to the tube. The height of the liquid column is a function of time and denoted $h(t)$.

1.1 Applications of capillary transport

As previously mentioned, there are numerous applications of capillary transport phenomena in engineering, daily life and science. Two technical applications shall be introduced briefly in the following section. The first one "Propellant Management Devices" describes the main motivation of this work, while the second one "Heat Pipes" concerns a system of major importance to thermal management of spacecraft .

1.1.1 Propellant Management Devices

In many spacecrafts and rockets liquid propellants are used as they typically provide a much higher specific impulse I_{sp} than solid propellants. The specific impulse can be regarded as change in momentum per mass of the propellant that is used. Consequently, a propulsion system with a higher I_{sp} is more efficient and will need less propellant to obtain the same Δv (change in velocity). For many cases the increased complexity and costs of liquid propulsion systems are more than balanced by their higher specific impulse.

However, the main problem in liquid spacecraft propellant tanks in orbit is the lack of gravity to define "up" and "down". When operating within microgravity, it can become difficult to separate the liquid propellant from the pressurant gas in the tanks. Despite this, a constant and gas free delivery of propellant to the engines has to be ensured during all acceleration conditions of the mission. To handle this problem, Propellant Management Devices (PMDs)

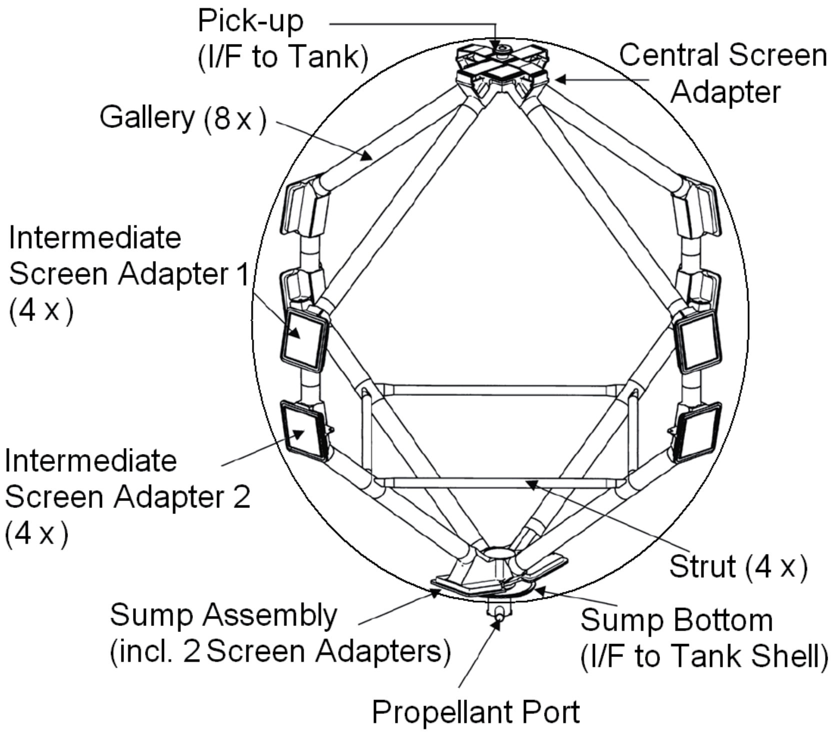

Figure 1.2: Total communication type Propellant Management Device (PMD) of the Automated Transfer Vehicle [8] including galleries with screen windows (slightly modified).

are utilized. These often feature a fine porous structure - like a metallic weave - which allows liquid to permeate but blocks out gas below a critical differential pressure. This phenomenon is known as the bubble point effect. Propellant Management Devices are designed to i) ensure a constant connection between propellant and tank outlet (communication type) or ii) confine the propellant at a designated location (control type) [1, 27, 82]. Fig. 1.2 shows a total communication type PMD including galleries with porous screen windows. These screens are made of metal weave and form passive surface tension devices. As mentioned they allow propellant to penetrate but prevent gas from entering below a critical bubble point pressure. This mechanism requires the weave to be always saturated with propellant. If a screen is partially dry, wicking can be regarded as a self healing mechanism to restore saturation. Here, the wicking performance strongly depends on the degree of evaporation from the porous screen. Especially for cases where the propellants are cryogenic liquids such as hydrogen and oxygen (as displayed in Fig. 1.3), the PMD may fall dry during coast phases, and require appropriate refilling and rewetting of the structure during subsequent chill down. This is the motivation for chapter 7 “Linear capillary rise and the effect of evaporation”.

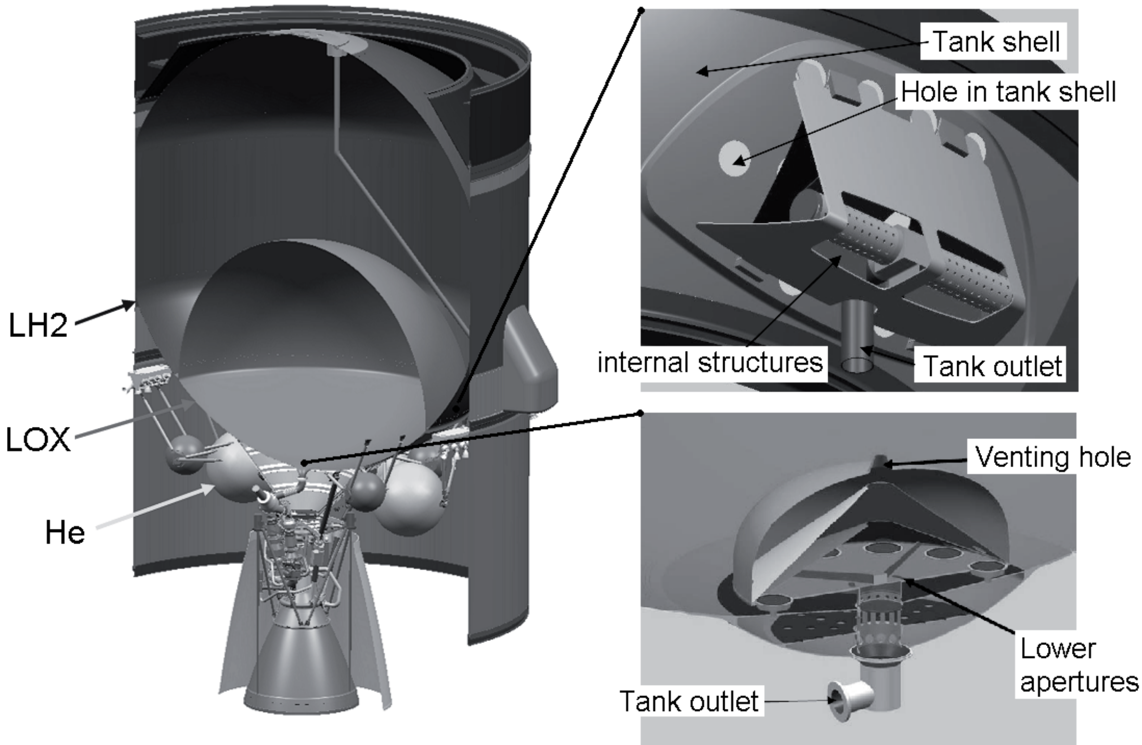

Figure 1.3: Draft of the proposed Propellant Management Device for the new, restartable upper stage ESC-B for the European launcher Ariane 5 [7] (slightly modified).

Transport processes in porous materials are also of great interest to determine material properties which affect relevant parameters including cross flow pressure and bubble point pressure. A better understanding of the occurring processes will enable engineers to identify better structures for usage in PMDs. These structures should provide several characteristics, e.g. have a high bubble point, however feature a minimal resistance against fluid flow (= a high permeability).

1.1.2 Heat Pipes

Heat pipes are passive devices designed to effectively facilitate the transport of heat from a hot heat source to a colder heat sink [103]. To transport comparably large amounts of heat they only require a fairly low temperature difference between the hot and cold interfaces. As shown in Fig. 1.4, a heat pipe evaporates liquid at its hot end. The resulting vapor is transported through the center cavity and condensates at the cold end, which provides heat transport due to the latent heat of phase change. The liquid however must return back to the hot end to close the loop. For this process, porous materials or structured surfaces are used which - due to capillary forces - transport the liquid back to the hot end to restore saturation (see Fig. 1.5). The advantages of heat pipes in comparison to conventional heat transport systems are not only the passivity and robustness. Due to their low thermal resistance they provide very high heat fluxes [W/m^2] based on their cross section. For a typical device length this results in a smaller system diameter and mass when compared to a block of copper for example. Working temperatures of heat pipes range from a few (5) Kelvin up to several thousand (2200) Kelvin. The choice of the working fluid strongly depends on the operating temperature range [103]. The following list provides a brief, incomplete overview:

- Cryogenic temperatures down to a few K: liquified gases like e.g. Helium (He), Hydrogen (H_2), Nitrogen (N_2).
- Cool temperatures below 250 K: Methane (CH_4), Ethane (C_2H_6).
- Moderate temperatures up to 500 K: Freon, Ammonia (NH_3), Water (H_2O).
- High temperatures: molten metals like Mercury (Hg), Potassium (K), Sodium (Na), Lithium (Li), Silver (Ag).

Due to their application in low temperature engineering, spacecraft thermal control, and electronic device cooling systems (see Fig. 1.5) - just to mention a few - heat pipes can probably be considered to be the most important devices featuring porous structures with capillary transport.

1.2 Embedment of this work in the frame of PoreNet

PoreNet is a Research Training Group (Graduiertenkolleg) funded by the German Research Foundation DFG. Several institutes from different disciplines participate in a collaborative and interdisciplinary effort to enhance the understanding of *Nonmetallic Porous Structures for Physical-Chemical Functions*. The aim of the work conducted in the Multiphase Flow Group at the ZARM is to investigate capillary dominated flows in porous materials to improve the comprehension and knowledge of the occurring processes and effects. This is conducted with a special focus on topics of relevance for the application of capillary flows in Propellant Management Devices as introduced earlier in this chapter. The underlying rationale is that an enhanced understanding of these topics will allow to design enhanced materials for these applications -

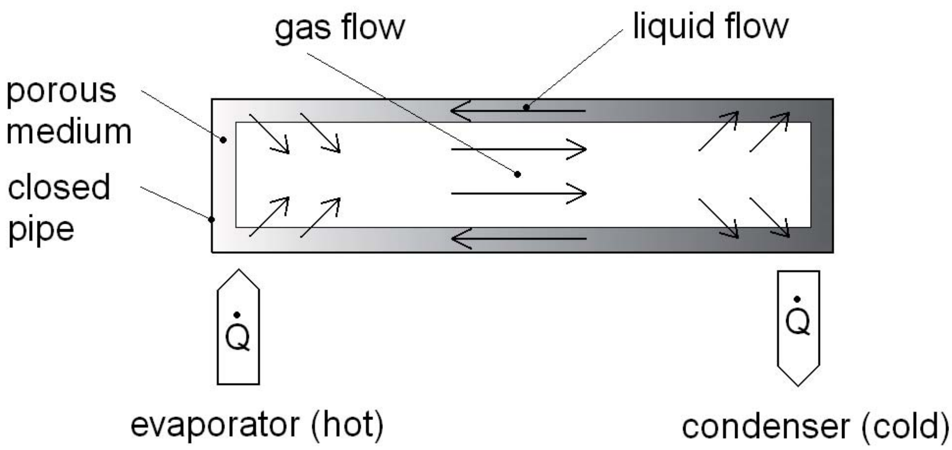

Figure 1.4: Schematic drawing of a heat pipe. Liquid is evaporated at its hot end (left) and condensed at the cold end (right). Capillary transport of liquid from cold to hot end.

which can be realized only in a design, production and testing loop in close cooperation with the other participating institutes. This present work is part of the first generation of doctorates in PoreNet and seeks to build the theoretical and experimental foundation concerning capillary flows in porous media for the works to follow. Relevant pore structure parameters and analogies to classic cylindrical capillaries are discussed in terms of analytical approaches and experiments as will be explicated in the next section.

1.3 Questions and aims of this work

The first part of this study is dedicated to a fundamental discussion of capillary flows. The aim is to enhance the understanding as well as the classification of capillary flows and the dominant forces by an analytical approach based on the governing equations. In chapter two of this work, the current "state of the art" of capillary driven flow is discussed and the main theoretical models, pore structure parameters, analogies and governing equations are introduced. The third chapter deals with a dimensionless scaling of the equation of motion. By this investigation the fundamental physics can be examined. Furthermore, the process of capillary dominated flow can be understood with a deeper insight than the dimensional consideration would allow. It also allows the classification of the rise process into different time stages under the impact of different corresponding forces. Chapter four investigates the transition from inertia dominated flow stage to the viscous stage during capillary rise. This helps to identify a priori the dominant forces that govern the flow. In the fifth chapter, analytical solutions including the gravity term,

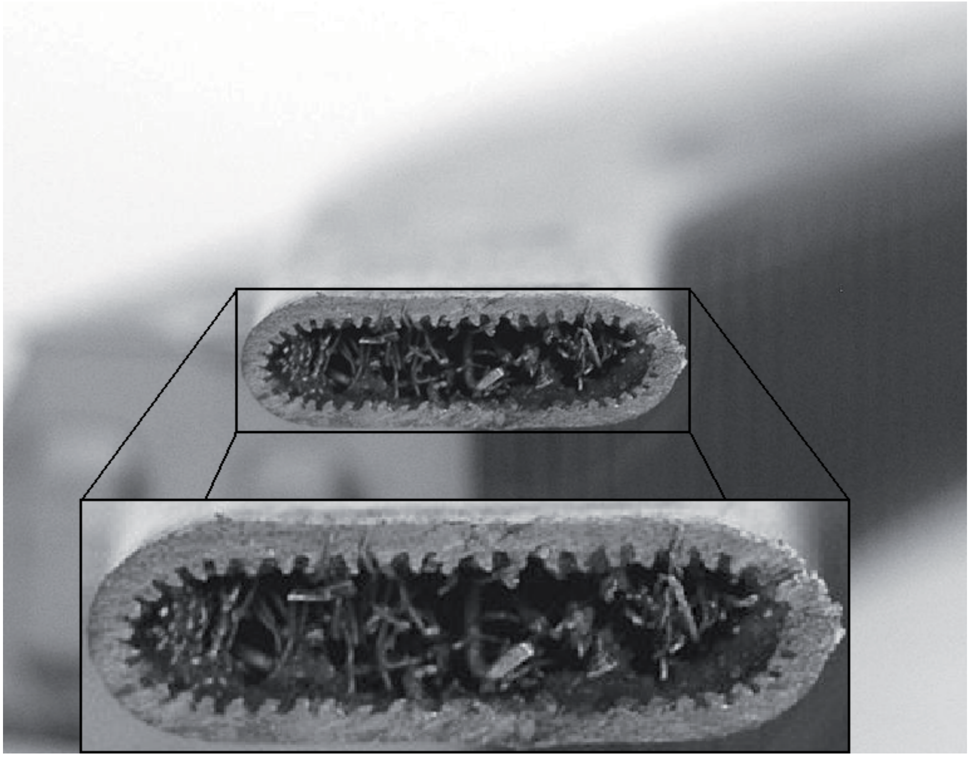

Figure 1.5: Cross section of a heat pipe used for cooling computer processors. Capillary transport is obtained by application of a grooved surface and copper gauze [108].

based on the implicit Washburn equation, are introduced. The discussion of the results allows to understand and predict capillary flows for an extended range of time. Some numerical simulations (CFD) and a macroscopic model of capillary rise is presented in the sixth chapter. The second part of this work investigates special cases of relevance to applications in spaceflight. The aim is to conduct fundamental research and to develop verified mathematical models that enable engineers to design enhanced PMDs. In chapter seven the linear capillary rise in thin, porous, metallic structures and glass filter frits is investigated. Also the effect of evaporation on capillary rise is determined. The interest arises particularly due to the actual development of a cryogenic, restartable upper stage (ESC-B) for the European launcher Ariane 5 (see Fig. 1.3). The eighth chapter discusses radial capillary transport in porous structures. This is in contrast to the previous chapters which all investigate linear transport. However, similar to the previous chapters a mathematical model is derived to describe the flow. An experimental setup for outward wicking is used to validate the analytical model. Thus, one is able to determine the validity of the derived solution and to discuss the assumptions made during the derivation of the model.