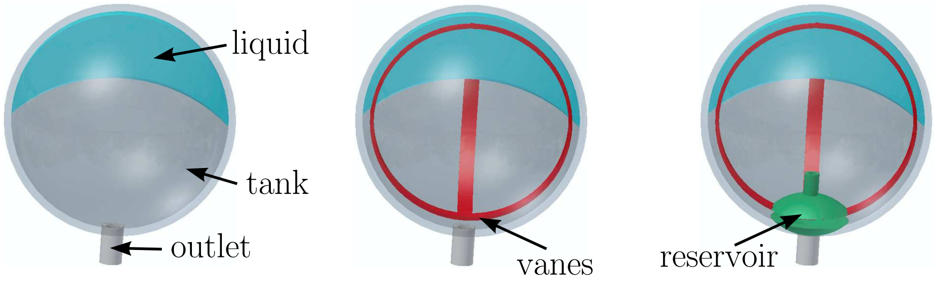
Chapter 1

Introduction

This study was conducted at the Center of Applied Space Technology and Microgravity in Bremen (ZARM, Germany). This institution is concerned with the development and scientific analysis of space technology and research in connection with microgravity. Within the research group "Fluid Mechanics and Multiphase Flow" there are three main subjects analysed to this end. Figure 1.1 illustrates them in their basic idea.



1) Position of liquid 2) Transport to outlet 3) Position at outlet

Figure 1.1: Liquid related to devices in tank

The first objective is displayed on the left-hand side, the behaviour of the propellant in microgravity has to be known within different conditions [36]. As second aspect, the liquid has to be transported reliably from an unfavourable position, e.g. farthest away from the propellant outlet, to the propellant outlet and from there to the thrusters. One of the common solutions to achieve this is displayed in the centre part of Figure 1.1, where vanes are placed near the tank wall. This is referred to as forced liquid transport in open channels [8]. The third subject is the trapping of liquid in the vicinity of the outlet during non-accelerated environmental conditions using refillable reservoirs as illustrated on the right-hand side.

The study presented here falls into the third category. The idea for this work was formed during some analysis concerning a study of a possible Propellant Management Device (PMD) for a reignitable Ariane 5ME upper stage [4,5]. A device like a PMD has to perform two major functions: One is the fast positioning of sufficient liquid. The other one concerns the trapping of the liquid at the propellant outlet, even during rotational manoeuvres (spin) to ensure a supply of a sufficient amount of propellant for a reignition of the thrusters. Figure 1.2 displays a design of a possible Ariane 5ME.

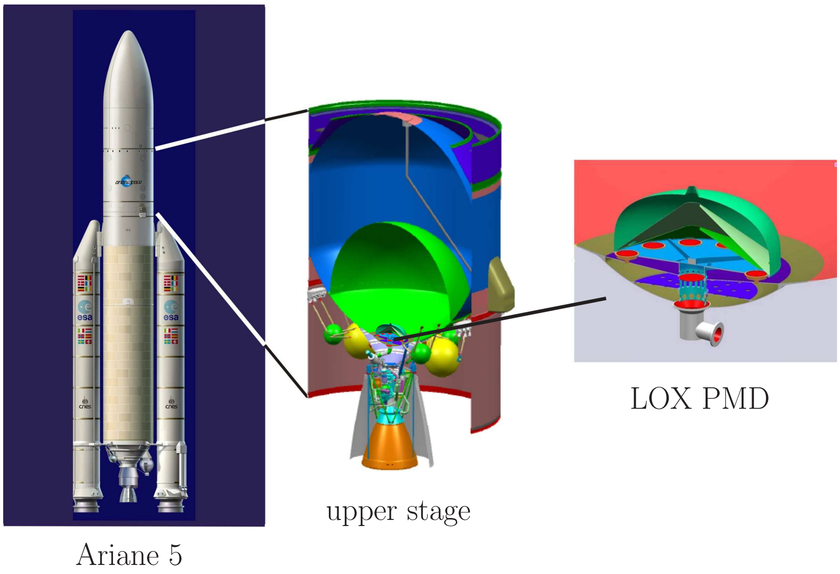


Figure 1.2: Schematic view of a possible Ariane 5ME, its cryogenic upper stage and a Propellant Management Device [4]

On the left-hand side, a drawing of the discussed Ariane 5ME is shown. In the middle the planned upper stage tanks are displayed with the LOX[1] PMD enlarged on the right-hand side. This PMD is responsible for the placement of the propellant. In microgravity, during the ballistic flight phase[2], the position of the liquid is dependent on the respective flight manoeuvre shortly before. In the worst case, the rocket induces a negative acceleration on the liquid. Therefore, shortly before the ballistic flight phase, the liquid might be located opposite the PMD at the top of the tank.

Since it is not feasible nor reasonable to place a multitude of pumps in the tank to ensure a transport of the liquid to the propellant outlet, one of the propellant's properties itsself is used to transport the liquid from the non-desired position to the desired position in the tank. The property in question is the surface tension. In the absence of gravity, the capillary forces become dominant and are used to position the liquid where it is required.

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[1] Liquid oxygen

[2] flight phase subject to no acceleration

PMDs take advantage of these forces to collect and hold the liquid like a sponge. Figure 1.3 shows the filling of such a PMD during a ballistic flight directly after an accelerated flight phase.

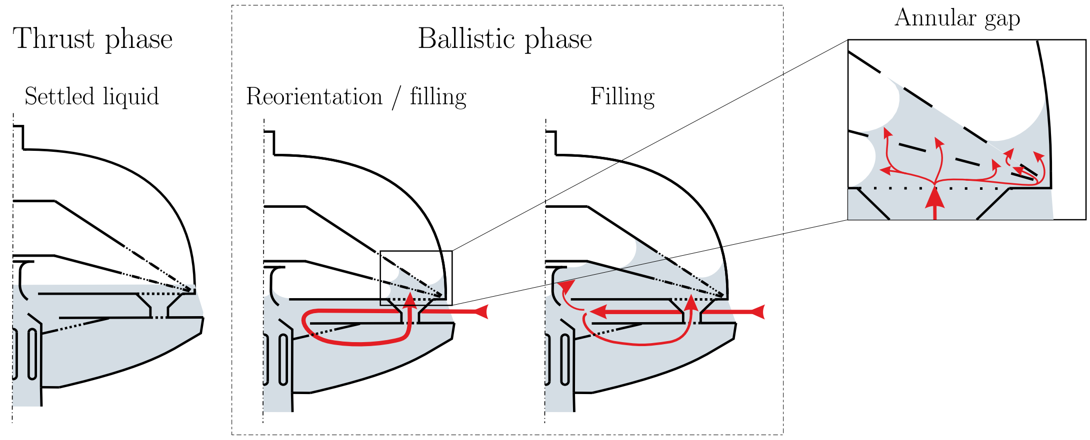


Figure 1.3: Schematic view of the filling of the studied LOX-PMD during the ballistic flight phase after a positively accelerated manoeuvre

During the accelerated flight phase the PMD behaves like an interference and induces an undesired pressure loss. Therefore it should be as permeable as possible in this flight phase. According to this reasoning, the fixtures in the PMD were designed to be perforated. An additional desired effect of perforations is the reduction of mass. The more perforations, the less weight and hence more mass which can be used as payload to be transported into orbit. On the contrary, when the PMD is used to position and hold the liquid, there should be as many solid surfaces as possible to achieve high capillary pressures which are used to transport the liquid.

During the preparation for an analysis concerning a potential PMD for the future Ariane 5ME it was found, that there is no research concerning the optimal placement of perforations to ensure a good compromise between permeability, fast filling and holding capability during all possible manoeuvres. For this reason, this present study was launched. To focus on the influence of perforations on the capillary filling behaviour, as a first step the secondary flow phenomena were reduced. Within the studied PMD the filling of the conical structures was from all sides (see Figure 1.3 on the right) and the conical structures induced a change of cross sectional area. Additionally, there are different flow paths present for the liquid to reach the conical structure.

Especially the multitude of flow paths presents a major issue for describing the influence of single parameters. Thus the geometry was adapted to accommodate only one main flow path with the entrance region placed on one side. To avoid the change of cross sectional area due to an opening angle the plates were placed in parallel. Figure 1.4 shows the resulting simplified geometry.

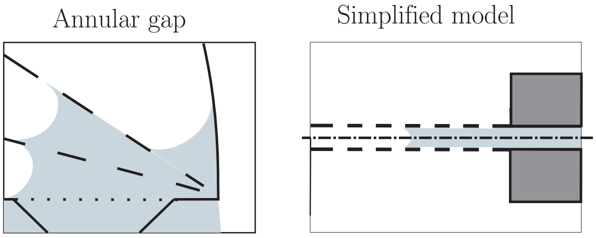


Figure 1.4: Simplified model of the perforated capillary transport devices in a PMD

This simplified model of the parallel perforated plates is subject of this study. The simplified geometry enables a detailed study of the flow phenomena induced by the perforations, since the capillary transport between parallel plates has already been analysed in the past [14, 18, 68].

During the analysis it was found, that the study of the capillary transport in this model has further impact on other research areas. Currently, the applicability of models in use for the calculation of effective contact angles on surfaces with different wettabilities [21] is discussed. The study presented here uses a model combination of classical theories to represent the change in surface structure of the solids due to perforations. This may be of interest to research in surface topology and coating applications.

A further area of research dealing with capillary transport in channels of varying cross sectional area and wettability of the transporting surface is the subject of micro channels in the field of electronics [62]. In this field, the wetting of structured surfaces is of major importance to cooling systems at small scale.

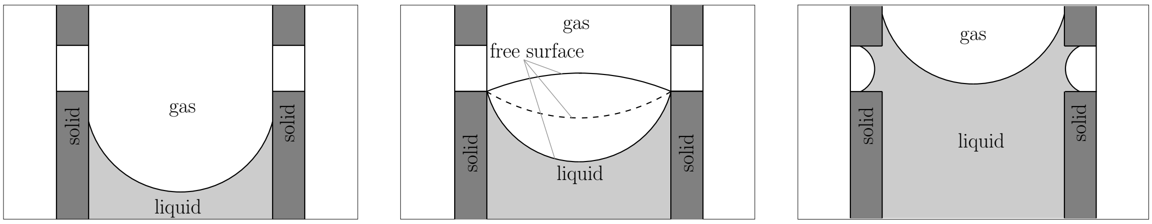
Other fields of interest are biological applications [38] and petroleum industry [7], where multi channel systems and counteracting capillary transport is more of interest than the wetting itself.

Chapter 2

State of research

In this chapter the scientific knowledge on which the author bases his studies is introduced. The following sections will introduce the known basics behind capillary transport of liquids between parallel perforated plates. When newer review papers are available it is omitted to recite all historical papers leading to the modern knowledge of the physical principles.

In an acceleration free environment, the capillary transport is mainly influenced by the contact angle of a liquid-gas interface on a solid. The main influences on this contact angle are introduced below (section 2.1). Governed by this contact angle, capillary transport of liquid between parallel perforated plates is separated in three physical processes. Figure 2.1 shows a schematic view of these different processes.



(a) Solid surface (b) Perforation edge (c) Imbibition into pores

Figure 2.1: Schematic breakup of the three main transport processes during capillary transport between parallel perforated plates

The first process is the “normal” capillary transport of liquid between walls. Here the contact angle functions as a boundary condition for the curvature of the free surface. This curvature results in a capillary pressure which drives the liquid flow (see section 2.2). When the free surface reaches the lower edge of a perforation the liquid is stopped at first. Further liquid transport does not occur until the liquid reaches the contact angle at the adjacent surface (see section 2.3). If the wall ended there, the liquid transport would stop without outside stimulation. Due to the three dimensional nature of the perforated plates the liquid can be transported around the perforation and therefore change the apparent contact angle at the pinning point at the lowest edge of a perforation. When the liquid spreads around the full circumference of the perforation, the walls of the perforation function as a capillary tube. At this point the transport of liquid not only occurs between plates but also inside the perforations. Now dependent on the plate distance (and to a slighter degree the plate width) and the perforation diameter, a prorated transport of liquid occurs along the plates and into the perforation (see section 2.4).

All three processes are well analysed separately in literature. Following, some of these studies are introduced and the underlying mechanics shown. Subsequently some related studies concerning numerical methods and the reasoning behind using Flow3D are introduced.

2.1 Contact angle

At the edge of a liquid on a solid surface in an ambient fluid (e.g. surrounding gas) a line is built, where all three materials come in contact to each other. This line is called contact line. At this contact line the considered liquid forms an angle related to the solid surface - the contact angle. The contact angle of a liquid is one of the main influences of capillary induced flow. Figure 2.2 displays how the static contact angle of a partially wetting liquid on a homogeneous surface within a gaseous environment is formed.

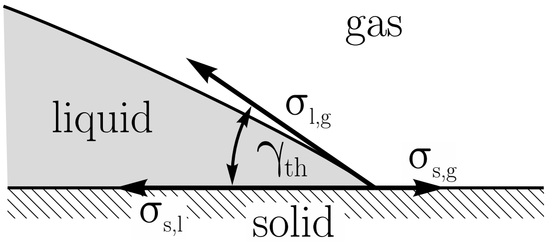


Figure 2.2: Vectors of surface forces and resulting static contact angle of liquid on a homogeneous solid surface

Using the vectorial summation of the forces at the different boundaries the static contact angle of a liquid on a homogeneous solid surface can be calculated using YOUNG's equation:

$$\cos \gamma_{th} = \frac{\sigma_{g,s} - \sigma_{l,s}}{\sigma_{l,g}} \quad , \tag{2.1}$$

with the surface energies $\sigma_{s,l}$ for the liquid-solid interface, $\sigma_{s,g}$ for the gas-solid interface and $\sigma_{l,g}$ for the liquid-gas interface. For $\cos\gamma_{th} > 0$ the liquid is considered as (partially) wetting liquid on this solid up to the limit of $\cos\gamma_{th} = 1$ where it is considered as perfectly wetting. If $\cos\gamma_{th} < 0$ the liquid is considered as non-wetting. In this study only wetting liquid-solid configurations are analysed.

This equation is only exact when two conditions are met: first, the contact line is not moving with respect to the solid surface and second, the solid surface is ideally homogeneous and smooth.

Moving contact line

When the contact line moves with respect to the substrate, the contact angle is not constant related to measurement position and velocity [53]. Concerning measurement position, it has to be distinguished between the microscopic contact angle, the macroscopic apparent contact angle and the intermediate region [6, 56]. Since the microscopic contact angle is measured in the molecular length scale it is not further investigated in this study, for further information on this subject see NAKAMURA *et al.* [47].

The macroscopic or apparent contact angle determines the curvature of the free surface when the length is the same order of magnitude as the capillary length [56]

$$l_\gamma = \sqrt{\frac{\sigma}{\rho\, g}} \quad . \tag{2.2}$$

For small gravitational accelerations (about 10^{-6} m/s^2) the capillary length is in the order of 1 m. Within a moving contact line, when the apparent contact angle is different from the static contact angle, the distinction is made by using the term ”dynamic contact angle“. The dynamic contact angle γ_D related to the CAPILLARY number can be calculated using [35] *section II.3* in radians for Capillary numbers less than 0.1 in an advancing contact line and a perfectly wetting liquid-solid configuration of $\gamma = 0°$

$$\gamma_D = 4.54\ \mathsf{Ca}^{0.353} = 4.54\ \left(\frac{v\ \rho\ \nu}{\sigma}\right)^{0.353} \tag{2.3}$$

with v the velocity of the liquid body parallel to the wall, ρ the density, ν the kinematic viscosity and *sigma* the surface tension of the liquid. In this study a perfectly wetting liquid is used between the plates and the CAPILLARY number is less than $2.2 \cdot 10^{-3}$ (see section 3.4). This gives a dynamic contact angle of $0° < \gamma_D < 30°$. This result shows an error of less than 15% for the calculation of the driving force during periods of higher velocity. In the study presented here, this influence of the dynamic contact angle is not taken into account.

For higher CAPILLARY numbers and partially wetting liquids KISTLER [35] *section II.3* introduces another relation. Both relations are confirmed recently by ŠIKALO *et al.* [55] for wetting liquids with Capillary numbers less than 0.1.

Non-homogeneous surfaces

Using YOUNG'S equation to calculated the overall contact angle requires the homogeneity of surface energy of the solid surface. For chemically varying or porous surfaces, other models have to be used. Considering a porous surface with an amount of A_P as "empty" surface area on an overall area of A, the area porosity at the surface can be calculated as:

$$\varphi = \frac{A_P}{A} \tag{2.4}$$

In such a case, the models used until recently were the WENZEL model [65] and the CASSIE model [9]. The difference between both models is displayed in figure 2.3. The WENZEL model considers filled pores. This holds true, when it is a case of a wetting liquid which is applied very slowly, the indentations are shallow (rough surfaces) or where the pores are connected. In this case the displaced fluid is assumed to be able to escape. The contact angle in the pores is then assumed to be 90°. According to the WENZEL model the effective contact angle can be calculated when dealing with a porous surface of the porosity φ using:

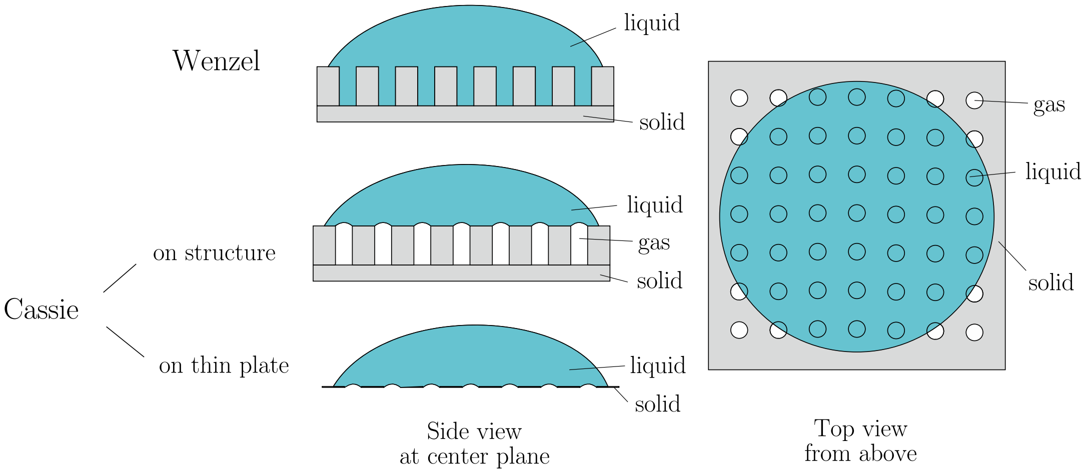


Figure 2.3: Liquid droplet on non-uniform surface considered with WENZEL model and CASSIE model

$$\cos\,\gamma_{efW} \;=\; (1-\varphi)\;\cos\,\gamma_{th} \tag{2.5}$$

With a perfectly wetting liquid, the term $\cos\,\gamma$ equals 1. Therefore, the resulting effective contact angle gives:

$$\cos\,\gamma_{efW} \;= 1-\varphi \tag{2.6}$$

In this case a non-wettable surface can not be reached due to structural changes.

Within the CASSIE model a surface is considered, where the displaced fluid is trapped in the pores or the pores are shallow and open (thin plate or layer of fibers). In this case, the contact angle in the pores is assumed to be 180°. This results in the effective contact angle on a porous surface:

$$\cos\,\gamma_{efC} \;=\; (1-\varphi)\;\cos\,\gamma_{th}-\varphi \tag{2.7}$$

With a perfectly wetting liquid of 0° contact angle, this gives:

$$\cos\,\gamma_{efC} \;=\; 1-2\,\varphi \tag{2.8}$$

In this case a non-wetting surface is reached, when the porosity is equal to or higher than 0.5.

One can be distinguish plainly between both models in a static situation. There it is obvious, if the pores are filled or not. Within both cases, partially filled pores are not considered. This assumption holds, when the pores are equally distributed on the surface and are much smaller than the considered contact line. These observations are presented in detail by GAO AND MCCARTHY [24]. They emphasise that the porosity at the contact line is of higher importance than the overall porosity for coarse structured geometries. After their publication, an ongoing debate started on the applicability and method of application of these two models.

More recently, VELLINGIRI *et al.* [60] discussed the wetting of chemically heterogeneous surfaces and found that even if their case falls in the domain of the CASSIE model, it does not explain the observed behaviour of the spreading liquid.

Yuan and Zhao [71] analyse the detailed process of the wetting on a pillared surface. It is shown, that a precursor film fills the pores in advance and the bulk of the liquid follows in its wake. Concerning the study presented here, this does not apply, since the pores are open and not connected, but it gives an insight about the advancement of the liquid.

The most recent overview on the wetting process on structured surfaces was published by Ramiasa [50].

2.2 Capillary transport between smooth walls

When the liquid is connected to not only one solid surface but two, at both solids a contact angle is built due to the surface forces. This contact angle defines the boundary condition for the shape of the free surface of the liquid. Since every surface tends to achieve its energetic most optimal state, the free surface of the liquid is curved to retain this boundary condition. If the two solid surfaces are parallel and there are no further forces present the curvature is circular with a radius of

$$r = \frac{a}{2\,\cos\gamma} \tag{2.9}$$

with the notation displayed in figure 2.4.

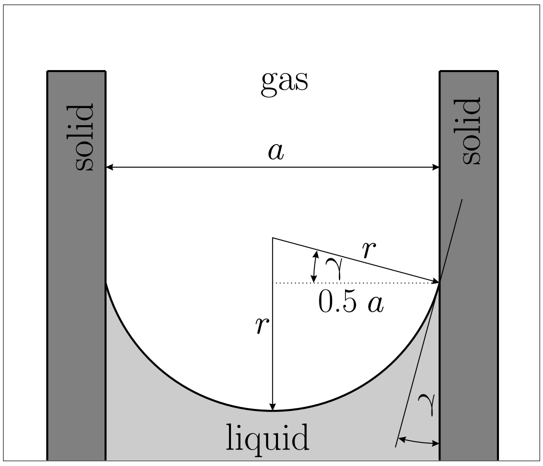


Figure 2.4: Curvature and capillary radius of a wetting liquid between two solid surfaces for a two-dimensional configuration

In a two-dimensional case with a defined as the distance between the solid bodies, this radius represents the capillary radius. The formation of this curvature results in a pressure difference between inside the liquid and outside the free surface. This differ-