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Capillary transport of cryogenic liquids in porous structures

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Chapter 1

Introduction

In this work the capillary driven transport process of liquids, especially cryogenic liquids in porous media is investigated. Since the liquid transport processes driven by capillary forces inside porous media are often called “wicking” [25, 61, 114], the ones with cryogenic liquids are usually called “cryo-wicking”. Cryogenics is the study of the production of very low temperatures (for example below -150 °C or 123 K) and the behavior of materials at those temperature. A few examples of typical cryogenic liquids are liquid hydrogen (LH2), liquid oxygen (LOX), and liquid nitrogen (LN2).

Fig. (1.1) shows a demonstration experiment of cryo-wicking. This experiment is performed in the laboratory with an open liquid container (a dewar) fully filled with liquid nitrogen under $1.013 \cdot 10^5$ Pa ambient air pressure at room temperature of around 20 °C and a piece of porous medium that is made out of glass frit. Fig. (1.1) shows a few obtained video snap shots recorded by a CCD camera and an infrared camera. As soon as the porous glass frit is brought into contact with liquid nitrogen, the liquid immediately wicks into the porous structure under the effect of the capillary forces and moves upwards, which is also a typical wicking phenomenon. While the initial temperature of the solid body is the same as room temperature, around 293 K (20 °C), LN2 has a temperature of approximately 77 K at 101.325 kPa air pressure. Heat transfer occurs between solid structures and liquids as soon as both parts come into contact with each other due to their large temperature difference. This results in a strong vaporization of LN2 until the solid structure is cooled to the same temperature as LN2.

While isothermal wicking without liquid vaporization in different porous materials has been a common investigation subject in the past [25, 74, 114], the processes involving vaporization are rarely investigated. Reports on wicking processes under non-isothermal conditions, especially with cryogenic liquids have not been found by the author in the literature yet.

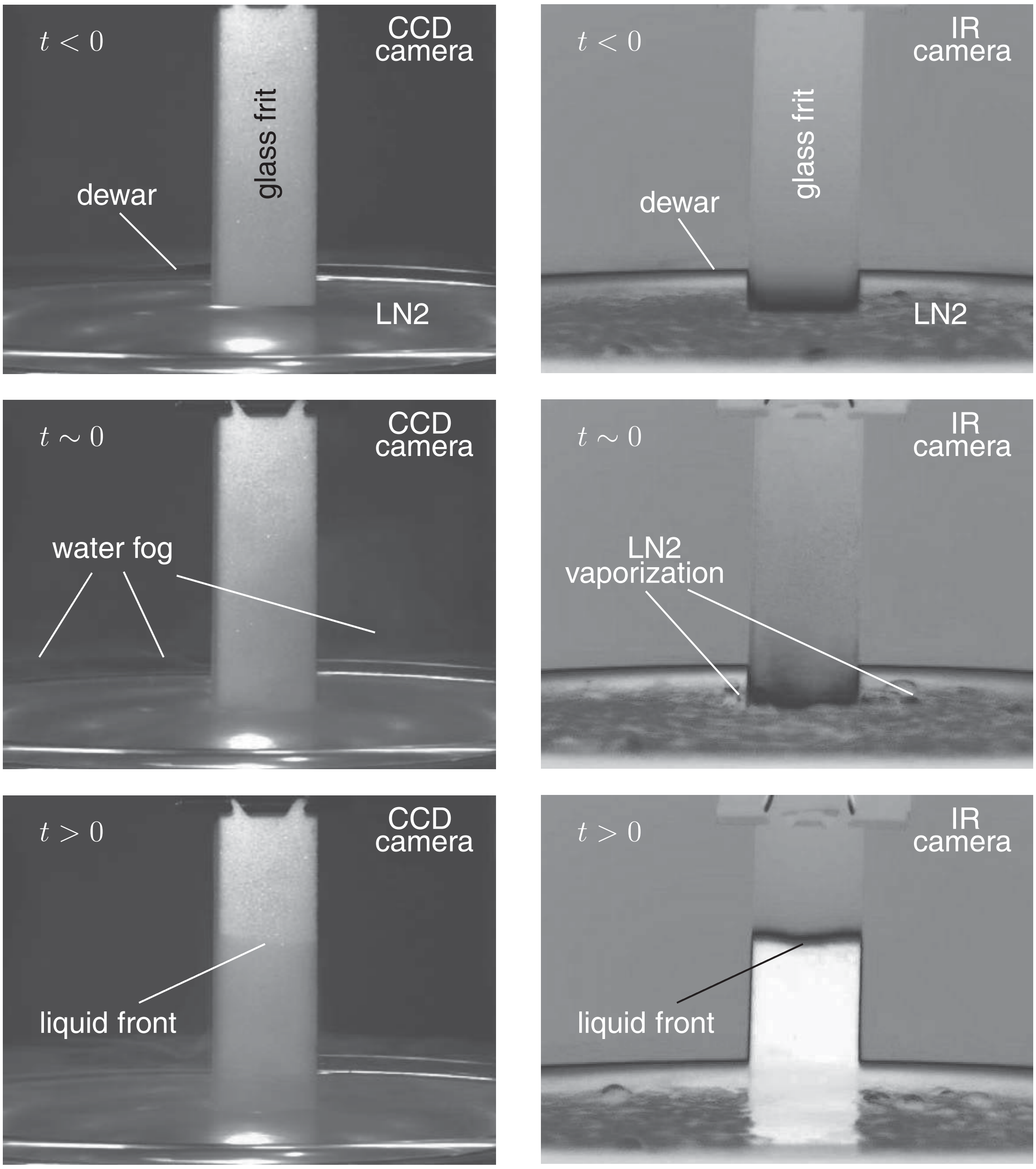

Figure 1.1: Video snap shots from both CCD camera and infrared camera during a wicking experiment performed with LN2 and a bar of porous medium made of glass frit. $t = 0$ is defined as the instant, when LN2 touches the glass frit. For $t < 0$ the glass frit moves downwards towards LN2. As soon as the glass frit touches LN2, a strong liquid vaporization occurs and liquid rises upwards along the glass frit. The infrared camera images show the temperature variation of the entire process.

Under isothermal conditions liquid vaporization will slow down the wicking process [40]. Under non-isothermal conditions the initial temperature difference between the solid structure and liquid leads to additional liquid vaporization in comparison to an isothermal wicking process with liquid vaporization. This work aims to identify the influence of this additional part of liquid vaporization, to understand, describe, and simulate the entire wicking process of cryogenic liquids, which occurs in a solid medium with a complicated microscopic irregular surface geometry including not only mass and heat transfer but also phase change.

1.1 Motivation and background

While the liquid positioning and liquid-gas separation process on earth remains an easy task due to the dominance of gravitational forces, the situation becomes very different in space as a result of the lack of gravity. In space technology, for example, for the upper stage of a rocket, the thrusters might be deactivated for a while and need to be restarted again later. In this scenario gas free propellant delivery to the thrusters is of great importance. If the tank outlet is not covered by propellants during restart, restart will fail because of gas ingestion. On the other hand, if gas bubbles are mixed in the propellant, they could cause serious damage or malfunction.

Usually, two methods are used to solve this problem in space technology. The first is an active method, where a short time acceleration is created with the help of additional engines, which employ, for example, gaseous propellants. This short acceleration process affects liquid similar to how gravity does on earth. The liquid is then positioned opposite to the acceleration direction and gas is separated from the liquid. Once the engine restart succeeds, a continuous acceleration is created, which ensures the further liquid positioning and gas separation process. This method is usually referred to as “settling”. However the valuable gaseous propellants are usually reserved for the use of attitude control and not available for engine restarts. The second method is a passive one, where an additional device is placed inside the propellant tank over the tank´s outlet. This device is usually called a “Propellant Management Device” (PMD) or “Liquid Acquisition Device” (LAD) [6, 29, 93], an example of PMD is presented in Fig. (1.2).

For the proper functioning of PMDs porous elements are often employed due to the existence of the two phenomena named “wicking” and “bubble point”. As mentioned

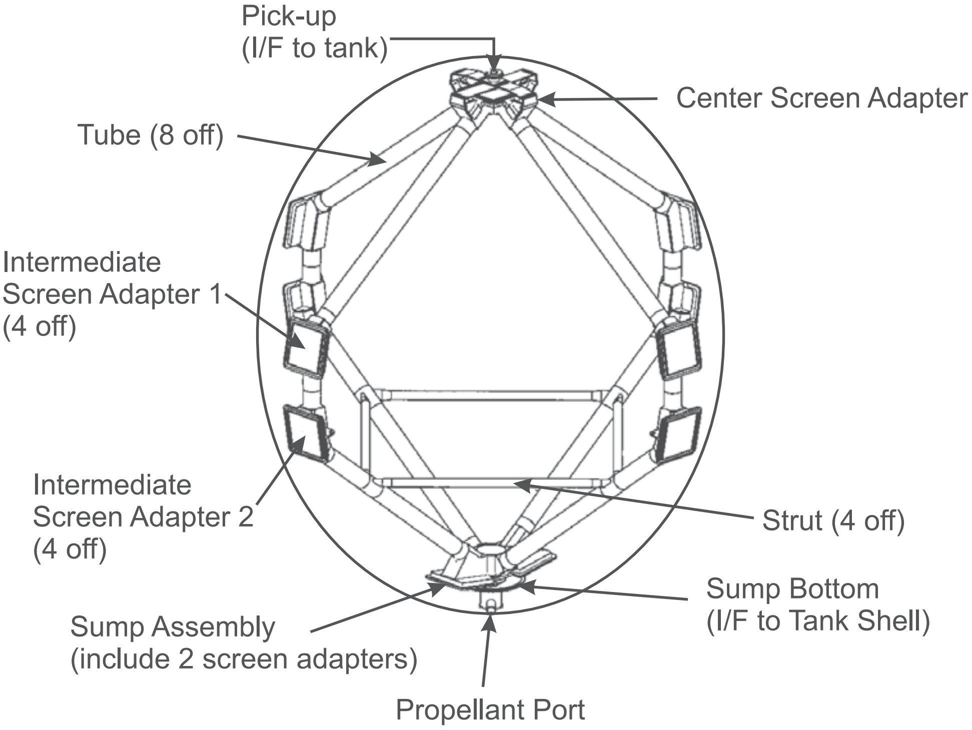

Figure 1.2: The PMD applied in ATV (Automated Transfer Vehicle) with screen elements made of porous media [12] (slightly modified).

previously, wicking is used to describe the liquid imbibition process induced and driven by capillary forces in porous structures. In general, if gravity is absent, capillary forces become dominant in the liquid transport process inside porous media. As a result of the wicking effect, liquid will automatically be transported through porous media from wetted areas to dry areas until the entire medium is saturated. While a porous structure is dry, both liquid and gas can enter and pass through it freely. However, if it is saturated by liquid, gas will not be able to enter or pass through unless a defined pressure is reached. This gas break-through pressure is called “bubble point” pressure, which depends on the combination of liquid and structure of the porous medium [23, 29, 58, 63]. By a proper choice of porous elements and suitable design of PMD the gas free propellant delivery can be achieved during all mission phases.

In fact, the application of PMD is not a new but a state-of-art technology in space industry [6, 23, 29]. However, up to now most PMDs only function with storable propellants. Storable propellants are those propellants which are liquids at the working pressure and temperature ranges, and remain liquids. Therefore they are called “storable”. For PMDs working with storable propellants, once the porous elements are saturated by liquid propellant a complete or local dry-out is not likely due to the liquid transport effect of wicking. But for liquids with high evaporation rates dry-out might take place if the wicking rate is too low. Propellants employed in space technology, that have high evaporation rates are usually liquid hydrogen (LH2), liquid oxygen (LOX), or liquid methane (LCH4), which are all cryogenic liquids with saturation pressures similar to tank pressure [29].

Despite the high evaporation rate and difficulties of handling, cryogenic propellants are always favored in space missions due to their high performance. Tomsik declares in his work [116] the four most desirable characteristics for high performance in space as **a**) high energy, **b**) high density, **c**) good heat capacity for cooling, and **d**) fast mixing and rapid combustion kinetics. According to Tomsik, LH2 is to date the only known propellant with all of these advantageous features with the exception of not having a high density. The combination of LH2 and LOX is traditionally widely used in the first mission phase of a space exploration to provide lift power. A well known example is the huge orange LH2 launcher tank of the Space Shuttles. Conversely, they are rarely applied for on-orbit propulsion due to the difficulties of handling, such as transport and storage. In the past years the environmental concerns have lead primarily to the examination of other non-toxic energy sources such as hydrogen for on-orbit propulsion, since the emission of environmental harmful combustion products of hydrogen with oxygen are zero. Nonetheless, it is more advantageous to store hydrogen or oxygen in liquid phase. Mital demonstrates an example of volume benefits of this [81]: Gaseous hydrogen stored at 35 MPa and 20 °C has only one third of the energy content per unit volume of liquid hydrogen. Tomisk states that cryogenic propellants are crucial for the future space exploration because of their superior specific impulse capability [116]. Doherty et al. [31] call the application of LOX/LH2 combination even as “an enabling technology” for the lunar mission, since the Altair [1] Descent Stage must utilize liquid oxygen/liquid hydrogen propellants, according to multiple engineering analysis and trades.

Due to their special characteristics compared to traditionally applied storable propellants, ongoing research from NASA is developing new techniques of handling cryogenic propellants for on-orbit propulsion. Mustafi et al. [84] and Moran [82] investigate the storage problem of cryogenic propellants. Dodge et al. [30] focus on zero-g [2] liquid quantity gaug-

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[1] Altair was the planned future lunar lander and part of the NASA´s project named Constellation. However due to announced cancelation proposal of U.S. President Barack Obama in 2010, it is not sure, if the development of Altair will be continued in future.

[2] Under weightlessness the gravity (g) is 0, therefore zero-g (0 g).

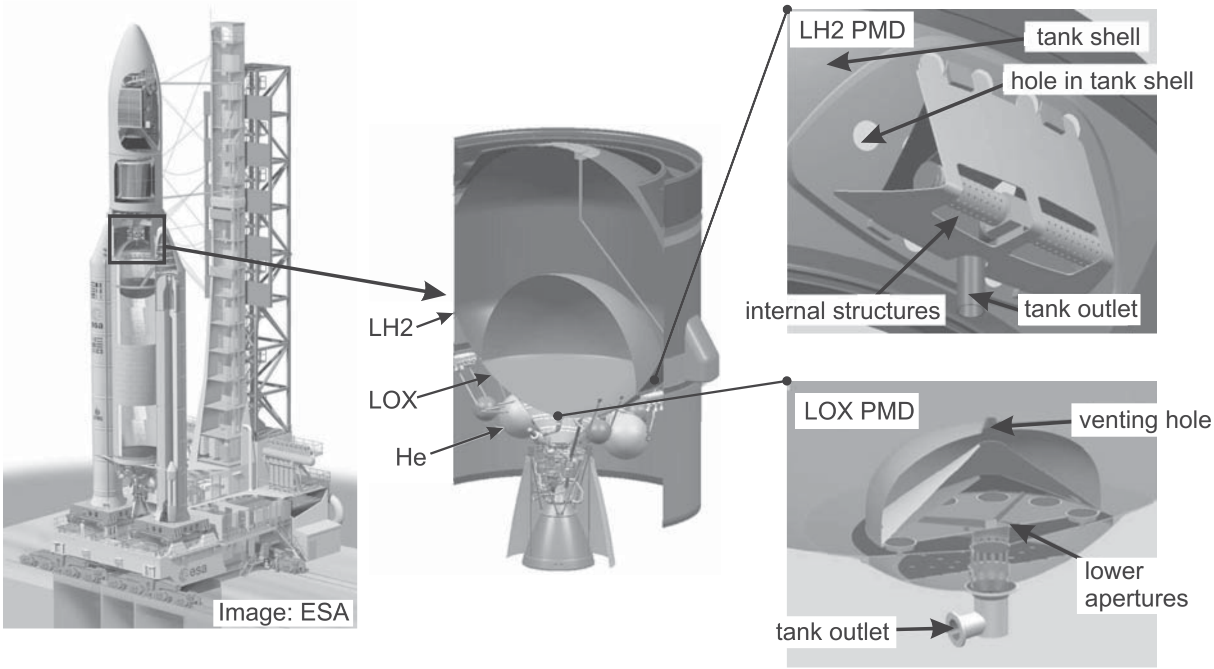

Figure 1.3: New and restartable upper stage with cryogenic propellants proposed by EADS Astrium for the European launcher Ariane 5 (A5ME) [10, 11] (slightly modified, image for Ariane 5 is cited from website of ESA [2]).

ing. Lopez et al. [70] deal with tank pressure control problems. Greene et al. [47] and Tomisk [116] try to develop new technology of propellant densification in order to reduce the propellant volume. Jurns [58] reports his work on bubble point determination with cryogenic liquids. The developing of new PMDs, which function with cryogenic propellants are reported by Chato [22], Chato et al. [23], and Jurns and McQuillen [57]. Tramel and Motil have given a good overview of these recent research activities of NASA under the project name "Cryogenic Fluid Management Technology" [83, 117].

This work is motivated by the previously mentioned recent research with cryogenic liquids, which are related to developing new PMDs managing cryogenic propellants (see Fig. (1.3) for a possible new cryogenic PMD design suggested by EADS Astrium [10, 11]). The reader might notice that the liquid used in the demonstration experiment of Fig. (1.1) is liquid nitrogen, which can not be used as propellant. However, LN2 has very similar physical properties to the common cryogenic propellants such as LH2 or LOX. In addition handling of LN2 is less dangerous because an explosion is not possible. Due to the high similarities of the physical properties between these cryogenic liquids, the research results with LN2 are supposed to be similar to those for LH2 or LOX. The application of liquid nitrogen as a replacement for the explosive cryogenic propellants is already widely practiced by other researchers involved in the handling of cryogenic propellants (see for example [22, 23, 58, 63]).

1.2 Contents of this work

The author reports in this work all knowledge obtained during the investigation of wicking processes with cryogenic liquids. It can be divided into three parts: Theoretical modeling, experimental investigations, and numerical simulations.

Theoretical modeling aims at the mathematical description of cryo-wicking processes where the solid structures have an initially different (higher) temperature than the liquid. A successful theoretical modeling helps to achieve a better understanding of the wicking processes as well as identifying the differences between cryo-wicking and the common isothermal wicking process. Parallel to theoretical modeling experimental investigations are designed and carried out, whose results are employed to validate results of the theoretical modeling. On the other hand these experiments can also serve as benchmarks for future numerical simulations.

Wicking processes with cryogenic liquids imply heat and mass transfer, phase change, and together with the microscopic irregular surface geometry they lead to a fact that a direct numerical simulation on the microscopic level (pore level) of a porous medium is impossible for large volumes with the computation power available. Therefore the author considers the realization of numerical simulations through a two step strategy. In the first step simulations are performed on the microscopic level, where the microscopic pore geometry is considered, and through which the macroscopic structural parameters, such as porosity, permeability, and static pore radius can be obtained. Once information of all macroscopic parameters are available, further simulations on the macroscopic level are performed, where the microscopic surface geometry of the solid medium is neglected and the entire medium is considered as a macroscopic homogenous continuum with corresponding macroscopic parameters obtained through the aforementioned microscopic simulations.

In this work macroscopic simulations are performed under isothermal conditions and without evaporation effect and are validated through corresponding experimental results without evaporation. The final aim of the macroscopic simulations is however to compute evaporation effects under non-isothermal conditions, where the heat transfer between solid and liquid structure is also considered.

1.3 Connection to PoreNet

This work is done in the frame of PoreNet, a research training group (Graduiertenkolleg) funded by the German Research Foundation DFG. PoreNet aims to obtain a deep understanding of different effects related to nonmetallic porous structures, develop new porous nonmetallic materials, and extend their applications. The author is one of the second generation doctoral students of PoreNet, who focuses on understanding and describing the flow transport process, especially those related to capillary forces.

Because of the unavailability of ceramic porous materials (still under development) this work is performed with porous glass frits (see chapter 4), which are also nonmetallic materials and are supposed to have physical properties similar to the expected ceramic porous materials. Due to the physical similarities, the knowledge obtained with glass frits is assumed to be also valid for ceramic materials. The experimental and numerical methods developed in this work should also be transferable to the future investigation of ceramic porous materials once their development is done and samples are available.

This work continues the work performed by Fries [40], who was also member of PoreNet but one of the doctorates of the first generation. In his work Fries focused on the fundamentals of capillary driven transport processes. He performed the analytical investigations of capillary rising process and experimental investigations on wicking with volatile liquids under isothermal conditions.