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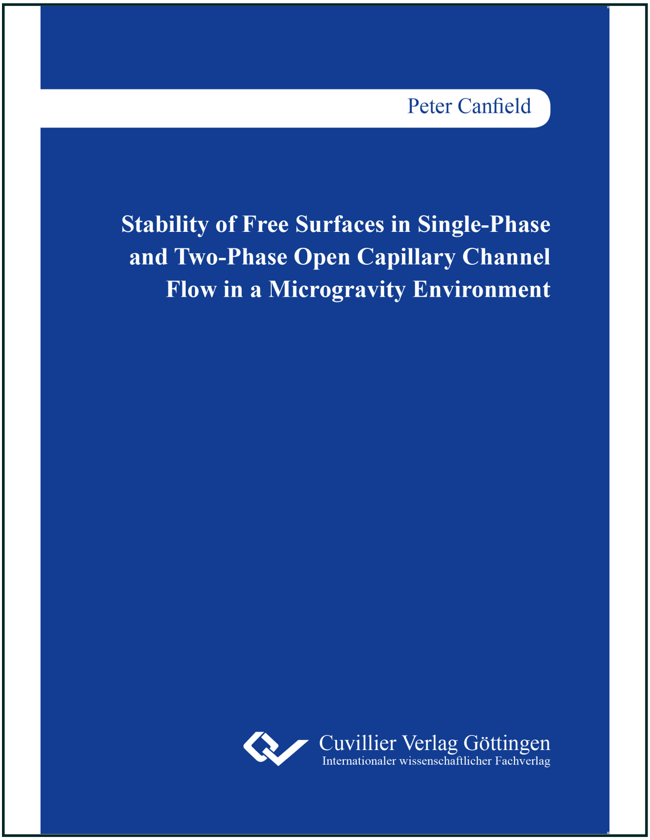
Stability of Free Surfaces in Single-Phase and Two-Phase Open Capillary Channel Flow in a Microgravity Environment



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Chapter 1

Introduction

Open capillary channels are structures that contain a liquid with one or more free surfaces (gas-liquid interfaces) and in which capillary forces dominate the characteristics of the flow rather than gravitational forces. This can be the case in environments where the influence of gravity is reduced in comparison to other forces or compensated, e.g. in space, but also occurs on Earth when the characteristic length scale of the flow is small ($\approx 10^{-3}\,\mathrm{m}$). The increased importance of capillary forces in a reduced gravity environment opens the door for passive transport and control mechanisms that rely on surface tension, wettability, and geometry to perform tasks that would otherwise require bulkier and heavier equipment or less reliable techniques involving movable parts [63]. For example, open capillary channels are used in propellant management devices (PMDs) of space vehicles to position and transport liquids within surface tension tanks. During acceleration phases the liquid bulk orients itself due to body forces acting on its mass, but during non-acceleration phases the liquid may distribute itself freely within the tank. Consequentially, the outlet of the tank may lose contact with the liquid rendering the remaining propellant in the tank inaccessible for further operations unless the liquid can be transported towards the outlet again. One of the purposes of PMDs is to prevent the liquid from becoming inaccessible. Surface tension tanks employ vanes, which are narrow and thin sheets of metal that may be positioned parallel or perpendicular to the tank's wall to form open capillary channels [31]. Using vanes to transport liquid from a bulk reservoir within the tank towards its outlet port is weight-efficient and increases the device's reliability. Similar benefits can be of importance in other liquid managements systems such as those used in a space vehicle's life support systems or storage tanks. Capillary channels are also used for managing liquids in micro-electromechanical systems for lab-on-a-chip devices [39, 69], effectively reducing the need for valves and pumps in micro-scale devices that are utilised in the biological and chemical industries.

However, previous studies [22, 31, 46] have shown that free surfaces can collapse and cause gas ingestion in open capillary channel flows when a critical, maximum flow rate, Q'_{crit}, is exceeded[1] (compare figure 1.1). This flow phenomenon is referred to as 'choking'. In reduced or compensated gravity, open capillary channel flows are subjected to changes in cross-sectional area due to pressure loss or gain in flow direction. The free surface of the open channel behaves like a flexible wall and the pressure difference between the liquid in the channel p'_l and the ambient pressure p'_a are balanced by the local capillary pressure difference induced by surface tension and the local mean curvature of the free surface. Viscous and convective pressure losses within the channel increase with the flow rate and lead to a higher pressure difference across the interface which in turn is balanced by an increase of curvature. If the flow rate is increased further, at some point the maximum mean curvature of the free surface is no longer sufficient to balance the pressure difference and gas ingestion occurs at the gas-liquid interface; the flow in the channel is choked. The critical flow rate is defined as the maximum flow rate before choking occurs.

In some applications, choking may be detrimental to the flow system due to the ingested gas bubbles. Alternatively, bubble generation may be desired in other flow systems and achieved passively in this way. Understanding the mechanisms of open capillary channel flow will help optimise designs that are now in use and may widen

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[1] With regard to notation, symbols for dimensional variables are distinguished by a prime ($'$) following the letter (e.g. Q'). Constants and dimensionless numbers or dimensionless variables are written without primes (e.g. Q).

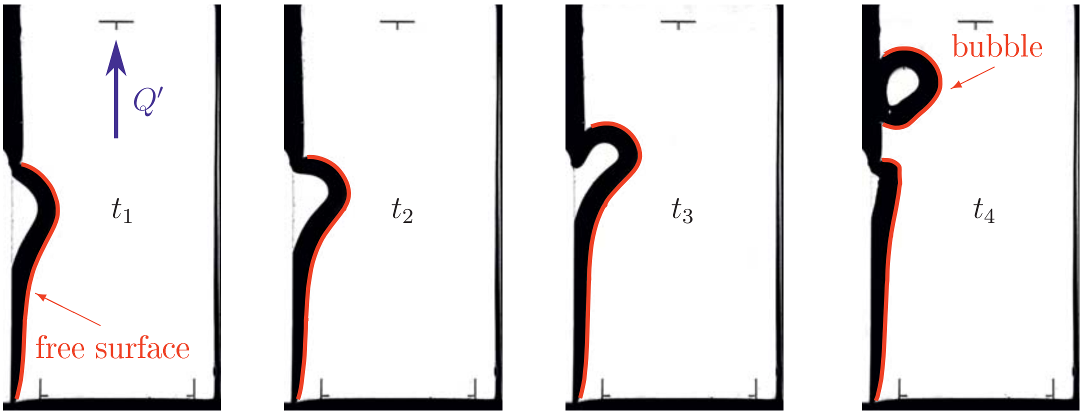


Figure 1.1: Time sequence of choked flow in an open capillary channel. Side view with flow from bottom to top. As time progresses from t_1 to t_4, the interface bends into the channel and a gas bubble is ingested.

the field of viable applications. It may be noted at this point that the presented capillary channel flow experiment is an ideal case with a simplified geometry, well-defined boundary conditions, and no residual acceleration (as far as can be provided on board the ISS). The actual situation in liquid management systems on a space vehicle may differ widely in terms of residual acceleration, geometry, and boundary conditions.

1.1 Scope

This work is concerned with the execution and analysis of experiments on flow rate limitation in isothermal, forced, single-phase and two-phase bubbly open capillary channel flow in a microgravity environment. It should be noted that forced capillary flow is considered here (i.e. via a pressure gradient that is generated by a pump) in contrast to capillary driven flow, in which the driving force of the flow is the capillary pressure flow of a propagating meniscus. The investigated test channel is displayed in figure 3.3. The channel's cross-section is an isosceles triangle and constant over its length l'. The triangular cross-section is defined by its height b and the opening angle 2α located in its vertex. The channel's base width a is defined as $a = 2b \tan \alpha$.

The test channel is open on one side along l' and is surrounded by a static gaseous atmosphere with a given pressure p'_a which is higher than p'_0, the pressure in the liquid at the inlet of the test channel ($x' = 0$). The liquid within the channel is fully wetting with a static contact angle of zero ($\gamma = 0°$) and is saturated with the surrounding gas to prevent diffusion. The flow rate Q' is constant for each experiment and set at the outlet of the channel, the pressure at the inlet is well-defined and assumed to be known. Under these conditions, the pressure difference between the gaseous atmosphere and the flowing liquid in the open channel is balanced by the curvature of the free surface in accordance with the Young-Laplace equation [12], in which the product of surface tension and curvature define the capillary pressure

$$\Delta p'_{cap} = -\sigma \left(\frac{1}{R'_1} + \frac{1}{R'_2} \right) , \tag{1.1}$$

where σ is the surface tension and R'_1 and R'_2 are the first and second principal radii of interface curvature, respectively. The interface is assumed to be symmetrical with respect to the $x'z'$-plane. Both Q' and l' are varied to determine the critical flow rate Q'_{crit} as a function of l'. Furthermore, a gas injection device is located at the inlet of the test channel which is used to observe the influence of bubbly, two-phase flow on the channel's flow rate limitation.

The gathered data is compared with numerical results that are produced with a previously published one-dimensional analytical model and with three-dimensional numerical simulations. In addition, the analytical model is modified to account for two-phase bubbly flow and a new model describing bubble formation in the supercritical regime is postulated. The intent of this thesis is to compare experiment results with those achieved through computational means with the intent of model verification. An overview of the experimental and numerical data that was evaluated to this effect is presented in table 1.1.

This thesis is structured in the following manner: First, an overview of past research in the relevant fields field of fluid mechanics is presented followed by a short introduction into surface tension and an overview of the various multiphase flow models. In chapter 2, the one-dimensional model for open capillary channel

Table 1.1: Overview of the presented data. 1P and 2P represent single-phase and (injected) two-phase flow respectively. Two-phase flow is understood here only as forced gas injection into the test channel in contrast to gas bubble ingestion that always occurs in supercritical flow. Flow is understood to be critical when the upper flow rate limit is reached.

	1P	2P	1P	2P	1P	2P
	subcritical flow		critical flow		supercritical flow	
Experiment	yes	no	yes	yes	yes	no
3D CFD	yes	no	yes	no	no	no
1D model	yes	no	yes	yes	yes	no

flow through an isosceles triangular wedge is presented. In the following chapters, materials and methods used to gather data in experiments and numerical simulations are described and all results are discussed and compared in chapter 6. Also, the supercritical flow domain is described and a new bubble formation model is presented and compared to experiment results in a rectangular capillary channel in chapter 7.

1.2 State of the Art

1.2.1 Open Capillary Channel Flow

Initial analytical work on the performance of vanes as propellant management devices was conducted by Jaekle [31]. In this paper, he demonstrates the aspect of flow rate limitation in open capillary channel flow through propellant vanes in a surface tension tank and compares the phenomenon to flow rate limitation in compressible flow within closed converging-diverging ducts or incompressible flow through closed ducts with elastic walls. All these duct flows have in common a non-zero $\mathrm{d}A'/\mathrm{d}x'$ term (or $\mathrm{d}\rho/\mathrm{d}x'$ in compressible flow) in the respective equations for mass conservation due to the non-constant nature of the flow path's cross-section or the density of the gas, respectively. Flow rate limitation in compressible flow is based on the speed of sound, or the speed of density waves. Likewise, in open capillary channel flows and flow through elastic tubes, flow rate limitation, or choking, is defined by the velocity of a longitudinal capillary wave, or put otherwise, the speed of area waves. Jaekle uses a one-dimensional model to predict flow rate limitations for T-shaped vanes assuming steady, fully developed laminar flow without accounting for the effects of area variation on the viscous term.

In similar fashion, the work of Shapiro [53] is noteworthy due to the presentation of an analytical model for flow rate limitation in elastic, collapsible tubes. Shapiro defines a Speed Index for incompressible flow through elastic tubes as the ratio between local flow velocity and long wavelength phase velocity. Choking in an elastic tube occurs when the Speed Index ratio reaches unity. Ultimately, both Shapiro and Jaekle use models to show that wave speed-based flow rate limitation, that is traditionally associated with compressible flow such as in Laval nozzles, can indeed occur in incompressible flow when channel area variations are possible.

Experiments on flow rate limitation in a capillary channel composed of parallel-plates were conducted by Dreyer et al. [22] and by Rosendahl et al. [45] using a drop tower facility to mitigate hydrostatic effects. Their findings substantiated the hypothesis that open capillary flows are subject to a maximum steady volume flux, or a flow rate limitation, beyond which gas ingestion occurs across the free surface. Additional experiments were performed on sounding rocket flights to increase the duration of the experiments from a few seconds to several minutes which allowed further observation of the supercritical regime in which periodic gas ingestion occurs. Rosendahl et al. [46] compared the experiment results of drop tower experiments and an experiment onboard sounding rocket TEXUS-37 with an improved one-dimensional model that incorporated both principal radii of curvature of the free surface. The numerical predictions for the profiles of the free surfaces were found to be in good agreement with experimental findings. In addition, it was shown that the Speed Index ratio as defined in [31] and [53] is indeed verified by experiment results.

Further experiments were conducted on sounding rockets TEXUS-41 and TEXUS-42 to determine the effect of channel length on the stability of the free surface [44, 47]. It was found that increasing the channel length at a fixed flow rate could also lead to choking in the capillary channel. The extension of the one-dimensional mathematical model to incorporate accelerated flows was also compared to experiments that were performed on sounding rocket TEXUS-42 [27, 28].

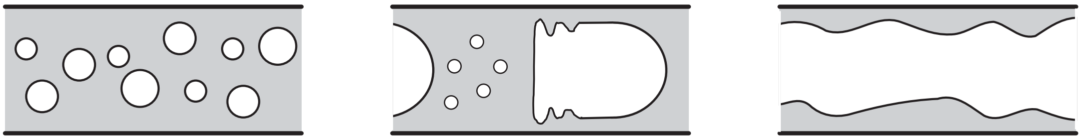
The influence of the shape of the channel's cross-section on the flow behaviour was investigated in further drop tower experiments. Critical flow rates were determined for a groove-shaped channel (i.e. parallel plates with one free surface walled off) and compared with the one-dimensional model by Haake et al. [30]. Klatte et al. [34] used the numerical tool Surface Evolver [7] to predict three-dimensional free surface profiles and flow rate limits of steady flow in a triangular wedge-shaped channel. The numerical predictions were in good agreement with those of the one-dimensional model adapted for a wedge-shaped duct and with the results of drop tower experiments [33]. Further drop tower experiments were performed by Wei et al. [62] using a similar triangular wedge-shaped channel. Their results confirm the findings of Klatte including the occurrence of flow separation at the free surface in CFD simulations.

Entering the regime of multiphase flow, Salim et al. [50] performed two-phase flow experiments in an open capillary channel on sounding rocket flight TEXUS-45. Bubbly flow was generated by means of a set of thin needles located upstream of the test channel. Based on their observations of the free surface profile in single-phase flow and two-phase bubbly flow, the authors concluded that wall shear stress increases when bubbles are injected into the flow stream.

So far, experiment data on open capillary channel flow has been thinly distributed across various channel geometries and flow regimes. Due to the restrictions of the experiment setups, large parametric studies were not possible outside of numerical simulations. Recently however, the CCF experiment on the International Space Station has generated a wealth of experiment data for three channel geometries and various flow regimes. A selection of the experiment results are presented and discussed in this thesis. Details of the experiment setup and the first results of the flow rate limitation experiments are found in Canfield et al. [13] including qualitative and quantitative observations of the bubble formation process in supercritical choked flow. A comprehensive review of the one-dimensional model for the open capillary channel with a rectangular cross-section is given by Conrath et al. [19], and its numerical results are compared with those gained from the ISS experiments with special attention paid to the differences between fully developed flow and plug flow at the inlet of the test channel. Bronowicki et al. [9] investigate the model for open capillary channel flow through parallel plates. After validating the model by comparing numerical results with experiment data the authors continue to study the model's predictions of the shape of the free surface within the steady, subcritical flow regime. Special attention is given to the transition between two flow regimes, in which pressure loss within the channel is predominantly attributed to either convective or viscous effects, respectively. The one-dimensional model is expanded by Grah et al. [29] to include transient effects and validated with experiments performed on the ISS. Additional experiments on passive, geometry-based phase separation were performed using the same setup and results are published by Weislogel et al. [64].

1.2.2 Multiphase Flow in Microgravity

One goal of this thesis is to determine the influence of a mono-disperse, gaseous second phase on the flow rate limitation that is evident in the single-phase experiments involving liquid flowing through an open capillary channel. The behavior of two-phase flows in closed pipes in microgravity has been the subject of various studies, primarily to determine flow pattern transitions and also to examine the influence of the second phase on the pressure drop within the channel. In both cases, the microgravity environment is of great importance. The behaviour of two-phase gas-liquid flows through pipes in normal gravity is influenced largely, if not dominated, by body forces acting on the dispersed phase. In reduced or compensated gravity environments, these forces are negligible and thus the variation of flow patterns and



Bubbly flow Slug flow Annular flow

Figure 1.2: Generic sketches depicting typical two-phase flow patterns through a closed, circular channel under microgravity conditions and with flow from left to right. The disperse gaseous phase is coloured white, the continuous liquid phase is coloured grey.

the typical conditions at which the respective patterns occur differ to two-phase flow in normal gravity.

Two-Phase Flow Patterns

In two-phase flow in closed channels, the flow pattern has a strong influence on the pressure drop that occurs within the flow. Consequently, it is important to determine or predict the flow pattern that will occur in the experiment. Dukler et al. [23] were the first to conduct a large number of experiments in drop tower experiments and parabolic flights to determine a flow pattern map for air-water flow closed duct flow in a microgravity environment. Three distinct patterns were identified with transition regions between them: bubbly, slug, and annular flow. Various papers are dedicated to determining appropriate dimensionless numbers that can be used to adequately differentiate the flow patterns of two-phase flow in microgravity. For example, further investigations on flow patterns of two-phase flow in microgravity were conducted by Colin and Fabre [17] (using air and water), Bousman et al. [5], and Zhao and Rezkallah [71] to name but a few. Experiment data available at the time is summarized by Jayawardena et al. [32], and a dimensionless flow pattern map is proposed for two-phase flow in microgravity based solely on the respective Reynolds numbers of the phases (based on the respective superficial velocities and viscosities) and the Suratman number ($\mathrm{Su} = \mathrm{Re}_L^2/\mathrm{We}_L = \sigma d_h' \rho_L/\mu_L^2$). In response, Vasavada et al. [61] recap various models to predict the transition from bubbly to slug flow in microgravity and conclude that the Suratman number shows promise in this regard, but stress that the void fraction ϕ should also be taken into account. They base their conclusion on observations from Colin et al. [18], who argue that the flow pattern transition depends on the pipe size and the physical properties of the fluids but should be independent of the superficial velocities. Colin et al. [18] propose that a critical void fraction can be used to predict the transition between bubbly flow and slug flow where $\phi = 30\,\%$ for $\mathrm{Su} < 1.7 \times 10^6$ and $\phi = 45\,\%$ for $\mathrm{Su} > 1.7 \times 10^6$. It should be noted that the experiment study of Vasavada et al. [61] was performed at low Reynolds numbers, therefore inertia was not a dominant force in the two-phase flow. In the majority of the experimental studies on phase transition, high Reynolds numbers were prevalent and therefore turbulent, inertia-dominated flows were examined. Woelk et al. [67] carried out a number of drop tower experiments to compare two-phase flow patterns and their transitions in normal and microgravity environments.

Most authors agree that further work is required to determine an adequate means of predicting the flow pattern transitions over a wide range of flow regimes. While flow patterns and their transitions are not of primary interest in this thesis, the flow pattern does have an effect on the choice of an adequate mode and on the pressure drop characteristics and it is therefore important to describe the flow regime appropriately. The two-phase experiments discussed in this thesis are situated within the bubbly flow regime.

Viscous Pressure Loss

Another focus of two-phase flow experiments in microgravity, and of some importance for this thesis, is the comparison of the single-phase and the two-phase friction factors. While no single model currently exists to accurately predict pressure loss under microgravity conditions, various studies have been performed to either modify existing normal gravity models, propose new models, or create approximate correlations based on empirical data. The predictions vary in their accuracy depending on