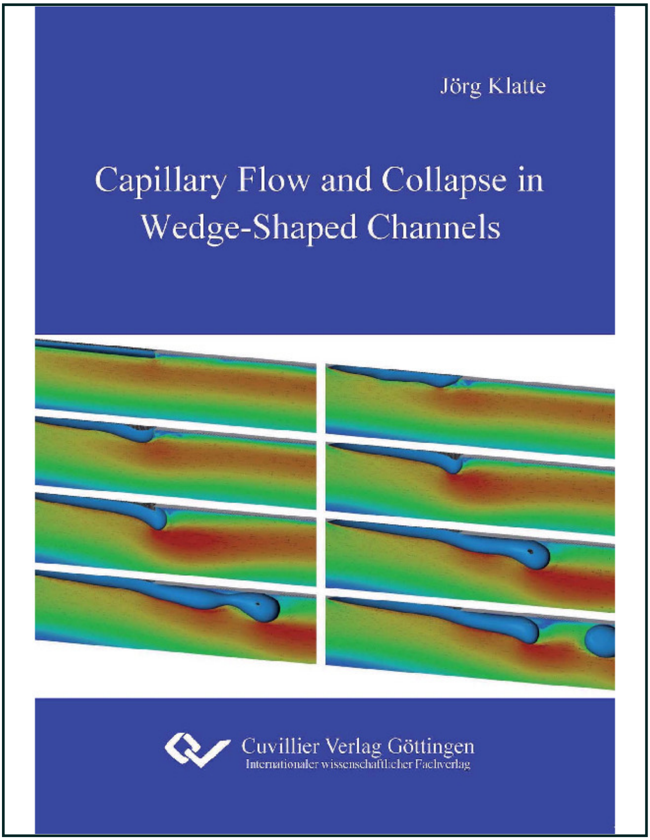
Jörg Klatte (Autor)

Capillary Flow and Collapse in Wedge-Shaped Channels



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Chapter 1

Introduction

In this work the laminar isothermal flow through an open wedge-shaped channel of length l, width a, height b, and half-corner angle

$$\alpha = \arctan\left(\frac{a}{2b}\right) \tag{1.1}$$

as sketched in figure 1.1 is investigated. The liquid flows along the x-axis from the inlet to the outlet and is maintained by an external pump with flow rate Q at the outlet. At the open side it forms a free surface. The study focus on surface-tension dominated systems at small Bond numbers and the curvature of the free surface dominates the flow behavior. The channel is surrounded by a passive gas phase of constant pressure p_a. At the inlet, the liquid pressure p_0 depends on the flow rate and is well-defined. At $x = 0$ the inlet pressure p_0 is smaller than the surrounding gas pressure p_a. In the presented applications, the liquid wets the channel perfectly with a contact angle of zero degrees. The free liquid surface is concave at any cross-section and deflects itself corresponding to the pressure difference between the gas and the liquid pressure p. Despite this fact the scaling and governing equations presented assume a constant contact angle γ at the walls and neglect any dynamic contact angle hysteresis. The origin of the coordinate system is at the bottom of the inlet. The variable k is a function of x and defines the distance from the corner to the midpoint of the interface. The Concus-Finn condition

$$\alpha + \gamma < \frac{\pi}{2} \tag{1.2}$$

is satisfied to avoid the breakup of the liquid stream into an array of droplets [16, 36, 79]. A volume force, due to gravitation or constant acceleration, influences the system. It is directed and quantified by the acceleration vector

$$\mathbf{g} = (g_x, g_y, g_z)^T . \tag{1.3}$$

The dependent dimensional variables for the critical flow rate Q_{crit} leading to a collapse of the free surface are summarized in table 1.1. This list defines the number of dimensional numbers of this problem to be introduced shortly. Since the flow is also dependent on the inlet pressure relative to the surrounding gas pressure and the flow history before the inlet and the outlet geometry, these values will be well-defined. In this work, the influence of the velocity distribution and the pressure distribution at the inlet and the outlet geometry on the critical flow rate Q_{crit} will be studied by changing the inlet and outlet geometries both experimentally and numerically. These boundary conditions will be explicit defined at the corresponding experimental and numerical sections.

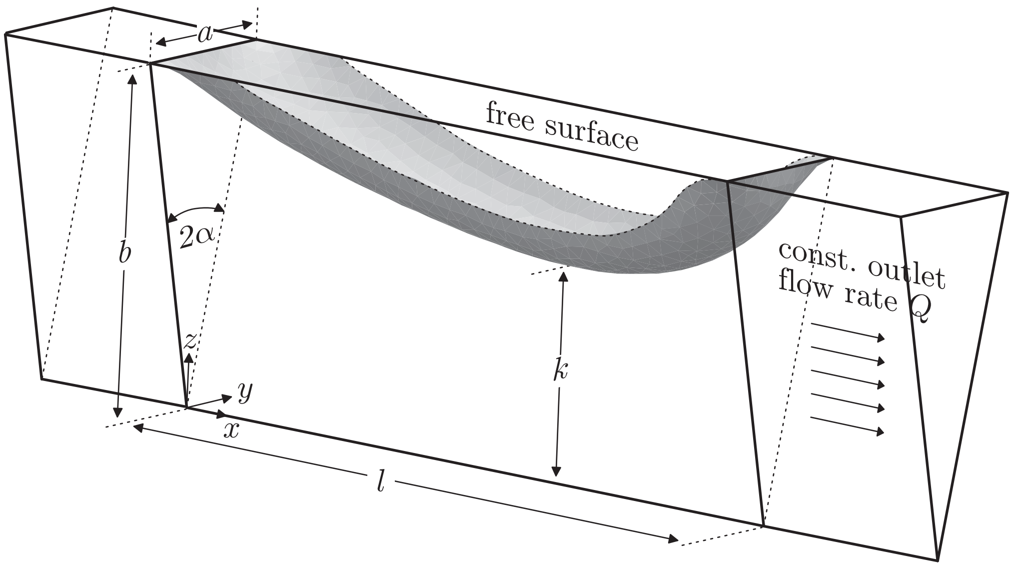

Figure 1.1: Schematic of the flow through an open wedge-shaped channel. The flow is forced by a pump with flow rate Q at the outlet. The liquid is surrounded by a passive gas phase with constant pressure p_a, which is greater than the inlet pressure p_0.

Table 1.1: Summary of the dimensional parameters for the critical flow rate Q_{crit} of a laminar and isothermal channel flow in figure 1.1. The flow history at the inlet is well-defined and the gas phase is passive.

dimensional parameters								
a	[cm]	width	μ	[g/(cm s)]	fluid viscosity	g_x	[cm/s^2]	x-acceleration
b	[cm]	height	ρ	[g/cm^3]	fluid density	g_y	[cm/s^2]	y-acceleration
l	[cm]	length	σ	[g/s^2]	surface tension	g_z	[cm/s^2]	z-acceleration
			γ	[°]	contact angle			

1.1 Motivation

The study of the presented flow problem is central to the development of fluid management in space, which has been important since the beginning of spaceflight. The term implies the ability to position and control both liquids and gases in specifically identified locations [3]. In the compensated gravity environment of an orbiting spacecraft the hydrostatic pressure decreases to very low values depending on the residual acceleration and surface tension forces can dominate the fluid behavior. Fundamental knowledge of the fluid mechanics of these capillary flows are very important since operational scenarios are not testable on earth and thus completely rely on analytical or numerical concepts [20]. On one hand, open capillary channels are widely used in space technology to control liquid and gas locations. Propellant management devices (PMD) in surface tension tanks of satellites use capillary channels for the transport and positioning of liquids [17, 18, 41, 56]. Additionally, capillary flows are critical to many important fluids management systems such as fuels storage systems, life support systems, and other materials processing in the liquid state [76]. On the other hand, the study of surface tension dominated flows is also essential for small-scale flows. The development of microfluidic applications, such as Lab-On-Chip technologies, has dramatically increased during the last years [12, 30]. Moreover, flat miniature heat pipes are shown to be very promising in the cooling of electronic component systems [31, 46, 70].

1.2 Scope of this Work

The scope of this work is to study capillary flows theoretically, experimentally, and numerically. The focus is the wedge-shaped geometry. To date, corner flow studies have neglected the curvature in flow direction to simplify analysis. In this work, the specific inlet and outlet conditions are part of the problem, since capillary systems are sensitive and mostly affected by it. Curvature along the flow direction is therefore essential for the solution of the problem. So far, corner flows with a forced flow rate by external means has not been considered in literature. For capillary driven flows the flow rate is a result of the position of the interfaces. This work introduces the flow rate as a parameter, as is common for applications in closed fluid loops. Indeed, the basic equations are the same and the flow rate can be extracted from the change of interface curvature. Nevertheless, if the flow is not driven by capillary forces a flow rate limit exits, which leads to a collapse of the interface.

The theoretical work is therefore concerned with the dependency of this flow rate limit to the other parameters. As mentioned, this limit has already been studied by Rosendahl for the parallel plate geometry [58] and Haake [29] for the groove geometry. Therein, the main focus has been the Speed Index in the inertial flow regime. But neither a large-scale parametric study of the critical flow rate, nor a sufficient scaling method to predict this value exists. Moreover, for viscous flows, Rosendahl's [60] one-dimensional numerical solutions in figure 2.5 show a non-physical curvature at the outlet, leaving the collapse behavior unanswered for viscous flows. The goal of the present theoretical work is to introduce a general collapse theory and scaling for the mentioned flow geometries, that is valid for both inertia and viscous dominated flow regimes, using the example of a wedge-shaped channel flow. The theory shall implement the Speed Index, consider the scaling of Weislogel [77] for viscous and slender column flows, and introduce the contact angle γ as a new parameter.

Experimental data of the collapse behavior for inertia dominated capillary corner flows does not exist in literature. The experimental study at small Bond numbers is restricted to microgravity environments or to small-scale experiments, with difficult optical access and manufacturing accuracy. Therefore, the experimental approach of Haake [28], using the free fall environment of a drop tower, shall be adapted to the wedge geometry. The investigations are supposed to focus on the free surface contour and the maximum flow rate through the channel to undergird the collapse theory and to benchmark the numerical work. Ground experiments at small Bond numbers show the impact of residual accelerations and different boundary conditions. Additionally, the experiment serves as a test for the upcoming Capillary Channel Flow (CCF) experiment on the International Space Station (ISS), which is introduced in the experimental part.

Besides the experimental work, the capillary flows are solved with state of the art numerical codes. The use of existing three-dimensional codes is not trivial, due to many numerical parameters. Despite continued advancements in computational methods, they require validation and significant computational effort for accurate solutions. This work is concerned with the development and validation of an accurate and sufficient solution method applicable to many capillary flow problems, that is useful for scientific studies and engineering design. In summary, the use and application of three-dimensional codes are optimized and validated for the study of capillary flows. The validated numerical tools are used for a large-scale parametric study of the critical flow rate. The goal is to filter the physical collapse regimes and to determine their dependencies on the dimensionless numbers of the problem. The combination of one and three-dimensional numerical approaches is intended to identify the limits of the theoretical assumptions and their effects. This is useful for a critical review of many flow studies with similar flow assumptions. Finally, the full understanding of the physical collapse behavior leads to the scaling of the problem and produces parameter-independent equations, which are immediately useful for engineering application.