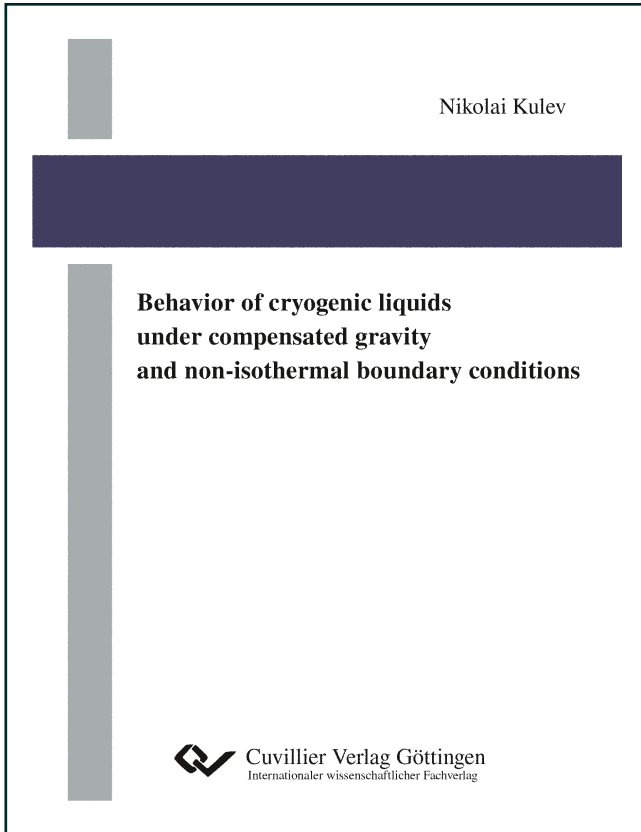




Nikolai Kulev (Autor)

## **Behavior of cryogenic liquids under compensated gravity and non-isothermal boundary conditions**



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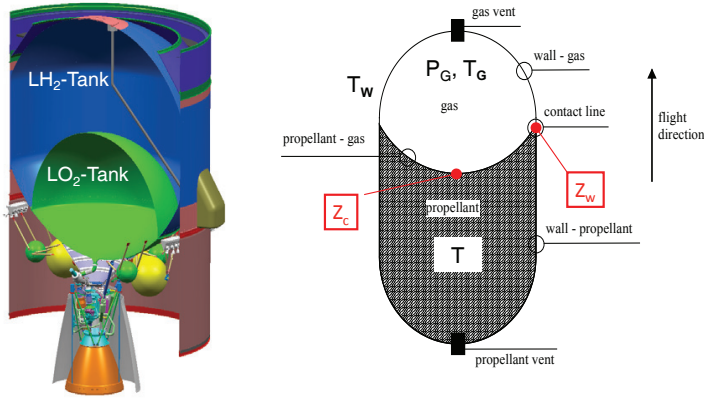
# 1 Introduction

Understanding the behavior of cryogenic liquids under reduced gravity and thermal influences from the environment is of great importance in the management of cryogenic propellants of the next-generation launchers. After the end of thrust of the engines the propellant is driven by the now dominating capillary forces from the steady-state position under normal gravity to a new steady-state position under microgravity, Fig. 1.1. Until the new steady-state position is reached, the interface exhibits decaying damped oscillations typical of underdamped systems and the whole process is known as interface (free surface) reorientation. During the reorientation the propellant moves along the warmer wall. Knowing the position of the propellant interface as well as pressure and temperature evolutions is crucial in handling the propellant during this ballistic phase.

The non-isothermal reorientation can be summarized in one sentence as following: step response of the liquid-vapor interface through capillary-driven flow with interfacial phase change. The general topic of the present work is the influence of the mass and heat transport on the linear impulse transport during the reorientation of the interface in a partially filled container under compensated gravity. So in specific terms the above summary of the reorientation can be reformulated as the influence of the interfacial mass flux on the interface dynamics and steady-state under  $\mu g$  through the corresponding boundary conditions at the interface and the contact line.

During the reorientation a transition takes place of the interface from its  $1g$  steady-state position under the action of gravity to its  $\mu g$  steady-state position under the action of capillarity and evaporation. Therefore I use two types of the mathematical description of the reorientation, Fig. (1.2). On the one side it is the fluid-dynamical description of capillary-driven flow with interfacial phase change, and with a contact line boundary condition explicitly accounting for the evaporation due to the wall superheat. On the other side there is the treatment of the phenomenon in the terms of the system dynamics - as a linear step response of  $2^{nd}$  order as in [58]. Thereby the focal point is the influence of the non-isothermal conditions on the fluid-dynamical and the system-dynamical quantities and parameters describing the reorientation.

After the step reduction of gravity the value of the contact angle is no longer equal to the value of the static contact angle  $\gamma_s$  but to the value of the dynamic contact angle  $\gamma_d$ . On the other side a reduction of the pressure occurs at the contact line due to the disappearance of the hydrostatic forces. So a capillary-driven motion



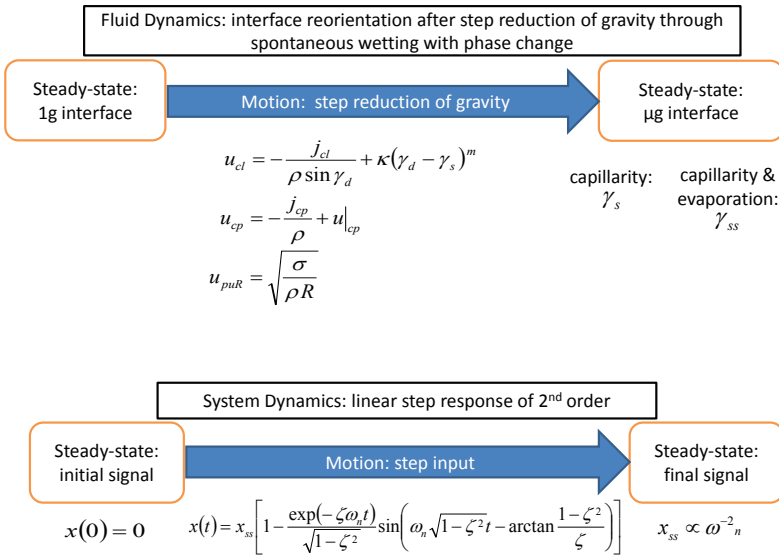
**Fig. 1.1.** Rendering of the Ariane 5 upper stage and a generic sketch of its tank. The tank wall, the propellant and the gas in the ullage have temperatures  $T_w$ ,  $T$  and  $T_g$ , respectively, and the gas pressure is  $P_g$ . The points of special interest from the interface between the propellant and the gas are contact line with a coordinate  $Z_w$  and the center point with a coordinate  $Z_c$ .

arises at the contact line due to both these reasons: the contact line begins moving towards its steady-state position corresponding to  $\gamma_s$  simultaneously with a flow from the liquid bulk to the contact line region due the pressure difference. Regarding the contact line boundary condition, containing the velocity of the contact line  $u_{cl}$  in Fig. (1.2), the difference between the dynamic and static contact angles  $\gamma_d - \gamma_s$  can be considered as a variable describing the capillary-driven flow, [17] and [8].

In this way the contact line is moved upwards the wall to regions where a significant difference between the wall and interface temperatures exists. At this point the action of the evaporation superimposes the capillary-driven motion. The mass flux at the contact line  $j_{cl}$  is the variable describing the action of evaporation on its motion [2]. So the contact line velocity  $u_{cl}$  becomes influenced by the evaporative term  $j_{cl}$ , too, besides the non-evaporative term  $\gamma_d - \gamma_s$ . In this manner the motion and the steady-state of the contact line become functions of the mass flux  $j_{cl}$ , too, when interfacial evaporation is present. The new steady-state is characterized by the contact angle  $\gamma_{ss}$  which is determined through the contact line boundary condition. This condition was used by [2] for the investigation of the influence of the evaporation from the interface and the contact line on the droplet spreading.

The motion of the center point is expressed through the interface boundary condition at the center point containing the velocity of the center point  $u_{cp}$  in Fig. (1.2). This velocity would be influenced by both the non-isothermal term with the mass flux at the center point  $j_{cp}$  and the isothermal term with the liquid velocity there  $u|_{cp}$ . This boundary condition is the equivalent of the mass balance boundary condition at the interface given by Eq. (2.27) and used by [64] for the investigation of the influence of the interfacial phase change on the capillary rise.

Due to the departure of the interface curvature from its steady-state curvature under isothermal conditions during the reorientation I assume that a capillary-driven flow with the characteristic velocity  $u_{puR}$  in Fig. (1.2) arises [81], [19], [50] which is the cause for the motions of the liquid and the interface.



**Fig. 1.2.** Basic features of the mathematical descriptions of the reorientation. Fluid dynamics: a motion due to capillary-driven flow with characteristic velocity  $u_{puR}$  with the interfacial phase change (mass fluxes  $j_{cl}$  and  $j_{cp}$ ), leading to a change of both the interface dynamics (velocities  $u_{cl}$  and  $u_{cp}$ ) and the  $\mu g$  steady-state (contact angle  $\gamma_{ss}$  instead of  $\gamma_s$ ). System dynamics: the square of the frequency  $\omega_n$  of the damped oscillations, until the final steady-state is reached, is inversely proportional to the steady-state deflection  $x_{ss}$ .

Therefore the presence of non-zero mass flux at the interface would turn the non-isothermal reorientation into a capillary-driven flow phenomenon with interfacial phase change. The influence of the interfacial phase change is manifested by variation of the interfacial mass flux in the corresponding boundary conditions at the

interface and the contact line due to the variation of the axial wall temperature gradients. This assumption is based also on the examples of the capillary-driven flow with interfacial phase change such as capillary rise and droplet spreading, which I summarize in Section. (2.5). The characteristic feature of these examples is the existence of the isothermal values of the quantitative characteristics of the dynamics and the steady-state of the interface. In the presence of interfacial phase change these values vary with the variation of the interfacial mass flux.

The above mentioned examples in the literature also show that action of evaporation is opposite to the action of capillarity [2], [64]. This means that evaporation either increases or decreases the above mentioned isothermal values, achieved solely under the action of capillarity. So the isothermal values of the reorientation characteristics based on the investigation on [50] should vary accordingly, too. Based on [2] and [64] the interface dynamics be interpreted as the mentioned competition between the capillarity and the evaporation, whereas the interface steady state can be regarded as their balance.

From the viewpoint of the system dynamics the reorientation can be approximated by a step response of a linear system of second order and the characteristics of the interface motion can be treated as the characteristics of this step response. The damped oscillations about the steady state deflection of such a system process exhibit a natural frequency  $\omega_n$  which is mathematically related to this deflection  $x_{ss}$  as  $\omega_n^2 \propto x_{ss}^{-1}$  [58], shown in Fig. (1.2). A variation of the wall superheat would result in a variation of the steady-state contact angle which in turn would lead to a variation of the steady-state deflection. Given the aforementioned relation between frequency and deflection a corresponding variation of the frequency would be expected too. So both the transient quantity (frequency) and the steady-state quantity (deflection) become functions of the wall superheat.

Up to the present moment the investigation of the liquid reorientation has been largely restricted to storable liquids in partly filled cylinders primarily only under isothermal conditions expressed by an adiabatic non-heated wall. The main results were achieved by [50] through experiments and by [29] through numerical simulations. The present study aims at the extension of the aforementioned results to the range of cryogenic liquids under non-isothermal conditions in the presence of a superheated wall. The influence of the interfacial mass flux on the reorientation characteristics is expected to manifest itself through the boundary conditions at the interface and the contact line, as already mentioned. The results by [50] and [29] show the influence of the contact line on the overall flow pattern in the liquid and on motion of the whole interface. Accordingly the variation of the contact line condition through the superheated wall should impact both the liquid flow pattern and the interface motion.

The present work has two major goals. The first one comprises the further development of the mathematical description of the reorientation used by [50] and [29] for the isothermal one-phase case to the non-isothermal two-phase case with pure liquids accounting for the wall superheat and the identification of the relevant dimensionless numbers describing the influence of the interfacial phase change on the



dynamics through the boundary conditions at the interface and the contact line. The second one aims at the experimental quantification of the influence of the variation of the mass flux at the interface and the contact line on the reorientation characteristics and the identification of the dependencies of these characteristics on the aforementioned dimensionless numbers.





## 2 State of the art and research goals

As already stated, the object of the present research is the reorientation of the liquid-vapor interface of the single-species, two-phase cryogenic liquids systems under non-isothermal wall boundary conditions and compensated gravity. The motion of an interface with phase change is investigated by its transition from one steady-state configuration under normal gravity to another steady-state position under micro-gravity through the capillary-driven process of spontaneous wetting.

The present work is the extension of the investigations by [50] and [29] of the isothermal reorientation. However, there is a clear connection of the present investigation to the physical mechanisms, mathematical formalisms and the results of other investigations as well. Accordingly, the task of present chapter is to present this connection, too, which can be summarized as: the influence of the boundary conditions at the interface and at the contact line on the interface dynamics in cases of a capillary-driven interfacial flow [81], both with and without phase change. In other words the variation in these boundary conditions would lead to a variation of the interface dynamics. This is apparent since the interface velocity appears explicitly in these boundary conditions. Accordingly the conditions can be viewed as a functional dependence of the interface velocity on the other dynamic quantities and constant parameters. So the above mentioned influence is expressed by these quantities and parameters or by the respective dimensionless numbers from the boundary conditions. Therefore the physical quantities and relations needed for both the definition of the boundary conditions at the interface and the contact line as well as the field equations presented in the next chapter are introduced here. This chapter presents also the research goals of the present work.

Physical mechanisms related to the liquid-vapor interface through the corresponding boundary conditions essentially influence the flow and the interface motion during the interface reorientation [81], [50], [29]. The knowledge of the action of these mechanisms and especially of their interaction is the foundation for the understanding of the reorientation process under non-isothermal wall boundary conditions. The two mechanisms which are considered here are capillarity and evaporation. The interaction between these mechanisms in terms of superposition and competition is assumed by me to be the basic underlying mechanism behind the non-isothermal reorientation based on [2] and [13]. The interaction between capillarity and evaporation can be quantitatively described by certain relations presented in this chapter.



Accordingly this chapter has the following structure. The steady state of the interface under capillary conditions is presented in Section (2.1). The definitions of interfaces, surface tension, static capillary interfaces and static contact angles are introduced there.

The contact line boundary conditions under isothermal conditions are treated in the next Section (2.2). For that purpose the dynamic contact angle and the dynamic contact angle relations are introduced there. The influence of the contact line boundary condition on the interface dynamics by the isothermal droplet spreading is given there. This influence by the isothermal reorientation and the isothermal damped interface oscillations is discussed in Section (2.6).

The phase change at the interface and the contact line is treated in Section (2.3). Relations of the interfacial mass flux due to the phase change (evaporation or condensation) are presented which are used for the formulation of the boundary conditions at the contact line in Section (2.4) and at the interface in Section (3.3).

The contact line boundary conditions with interfacial phase change are presented in Section (2.4). The steady-state value of the dynamic contact angle can be computed by one of these relations chosen by me as the boundary condition for the field equations in Section (3.3).

The capillary-driven flow with interfacial phase change is considered in Section 2.5. The influence of the phase change (mass flux or corresponding temperature difference) on the interface dynamics through the boundary conditions at the interface and the contact line is presented by the capillary rise and droplet spreading. The competition between capillarity and evaporation and its quantification are presented alongside with this.

Previous results concerning the reorientation of the interface from normal gravity to compensated gravity conditions and the damped interface oscillations under compensated gravity are treated in Section (2.6). As mentioned above the influence of the boundary conditions at the interface and the contact line on the interface dynamics are discussed in this section.

Finally, a synopsis and the goals of the present research are formulated in Section (2.7).

## 2.1 Steady-state interfaces under isothermal conditions.

As already mentioned the steady-state interface under capillary conditions are characterized by the static equilibrium of forces acting on the interface by the absence of any flow. Accordingly this interface can be termed as static, too. Under these conditions the contact line formed by the intersection of the interface with the solid boundary is also static. The angle of this intersection has a constant value which is termed static contact angle. The relations describing mathematically this physical situation follow.

### 2.1.1 Steady-state interfaces.

According to [10] an interface between the fluid phases is the boundary between the separate phases which under microscopic observation exhibits a finite thickness and is designated as interface boundary layer. The interface is characterized by a drastic change of a physical property (thermo-physical, optical, etc.) within the interface boundary layer from the value in the first phase to the value of the second phase. The thickness of the interface boundary layer between liquid and vapor at saturation is around 1 nm for normal liquids. For the purposes of my macroscopic investigation this thickness is much smaller than any relevant length scale so the interface can be regarded as a mathematical surface of an infinitesimal thickness, across which the physical properties of the phases exhibit a discontinuity. Physical properties are assigned to the interface which can be interpreted as mean values within the thickness of the interface boundary layer. Here I must point out that the boundary layer representation of the interface itself is entirely different from the microscopical interfacial boundary layers, both velocity and temperature, characterized by much greater thicknesses, with length scales of around 1 mm and more.

The fundamental physical property which characterizes the interface macroscopically and relates it to capillarity is surface tension. The thermodynamical definition of surface tension  $\sigma$  reads

$$\sigma = \frac{\delta G}{\delta A} \quad (2.1)$$

where  $\delta G$  is the change of the free energy of the system required for the increase  $\delta A$  of the surface area of the interface [57].

When there is no flow under the action of an volume force (gravity) the interface shape is governed by the Young-Gauss-Laplace equation relating the pressure difference across the static interface and its mean curvature [1]

$$P - P_A = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (2.2)$$

where  $P$  is the pressure on the liquid side and  $P_A$  is the ambient pressure. The quantities  $R_1$  and  $R_2$  are the principal curvature radii of the interface. The equation expresses the balance of normal stress to the interface by the lack of a tangential stress.

The quantity  $1/R_1 + 1/R_2$  gives the mean curvature of the interface with the corresponding radius  $1/R_m$ . The mean curvature radius is given [81], [50] for an arbitrary interface parametrized as  $h = h(x, y)$  in Cartesian coordinates by

$$\frac{1}{R_m} = \pm \frac{(1 + q^2)s - 2pqv + (1 + p^2)t}{(1 + p^2 + q^2)^{3/2}} \quad (2.3)$$

where  $p = \partial h / \partial x$ ,  $q = \partial h / \partial y$ ,  $s = \partial p / \partial x$ ,  $t = \partial q / \partial y$  and  $v = \partial p / \partial y = \partial q / \partial x$ .

Apparently the Young-Gauss-Laplace equation is so a nonlinear, partial differential equation containing second order spatial derivatives of the parametrization function of the interface. Accordingly one boundary condition is required at the

edge of a interface to have a well-posed problem. Usually this boundary condition is given by the static contact angle, prescribed where the meniscus intersects a solid surface, or seldom by the position of the contact line of the intersection [81], [17].

### 2.1.2 Static contact lines and angles

A contact line is formed at the intersection of two immiscible fluids and a solid. The mutual interaction between the three materials in the immediate vicinity of a contact line can significantly affect the statics as well as the dynamics of an entire flow field [21]. Under ideal conditions, a liquid at rest intersects a solid at a unique angle. The static contact angle  $\gamma_s$  is the angle at which the meniscus intersects the solid as measured through the liquid. In the case of a pure liquid the Young equation is valid in a thermodynamic equilibrium [28] giving the value of  $\gamma_s$ :

$$\sigma_{sv} - \sigma_{sl} = \sigma \cos \gamma_s \quad (2.4)$$

where  $\sigma_{sv}$  and  $\sigma_{sl}$  are the surface tensions of the solid-liquid and the solid-vapor interfaces, respectively. The above equation expresses the state of mechanical equilibrium due to the balance forces at the contact line. A special case of Eq. (2.4) is the complete wetting liquids with  $\gamma_s = 0^\circ$  ( $\sigma_{sv} - \sigma_{sl} = \sigma$ ), to which case the cryogenic liquids investigated here belong. In this case a liquid film of macroscopic thickness would be formed as an equilibrium interface on the solid [28]. Partially wetting liquids exhibit  $0^\circ < \gamma_s < 90^\circ$  and non-wetting liquids -  $90^\circ < \gamma_s < 180^\circ$ . In both cases  $\sigma_{sv} - \sigma_{sl} < \sigma$ .

It is found that the contact line remains motionless not just for the contact angle value  $\gamma = \gamma_s$  but for the interval  $\gamma_{sr} \leq \gamma \leq \gamma_{sa}$  [21]. A motion of the contact line occurs only if the contact angle value lies outside of the above interval. So the biggest value and the smallest value of the contact angle by which a motionless contact line is present are denoted as  $\gamma_{sa}$ , advancing static contact angle, and  $\gamma_{sr}$ , receding static contact angle, respectively. If the contact angle takes values  $\gamma > \gamma_{sa}$  an advancing contact line motion is initiated or wetting. By values of the contact angle  $\gamma < \gamma_{sr}$  a receding contact line motion begins and so dewetting. The presence of the interval  $[\gamma_{sr}, \gamma_{sa}]$  is known as contact-line hysteresis. It depends on the surface roughness of the solid, chemical contamination in the solid surface, solutes in the liquid [28].

## 2.2 Contact line boundary conditions under isothermal conditions.

The wetting process, the spreading of liquid over a smooth solid, represents a fundamental problem in fluid mechanics. It exemplifies the general problem of moving contact lines, which is encountered in such applications as the performance in Space of fuel tanks, mould filling and coating technology [24].

So the wetting behavior in the isothermal case is encoded with the constitutive equation relating the contact line velocity to the dynamic contact angle alongside