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Interface reorientation of cryogenic liquids under non-isothermal boundary conditions

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ABSTRACT

We investigate the capillary driven oscillations of the liquid–vapor interface in cryogenic systems under non-isothermal boundary conditions. The oscillations took place in a partly filled cylinder during the interface reorientation from its 1 g equilibrium position to the microgravity equilibrium position after a step reduction of gravity. The latter was achieved by dropping the experimental device in the drop tower of Bremen, providing 4.7 s of microgravity. Liquid argon ($T_{sat} = 87.3$ K at 1013 hPa) and liquid methane ($T_{sat} = 111.7$ K at 1013 hPa) were used as experimental liquids. Axial wall temperature gradients, corresponding to a linear increase of the wall temperature, were applied above the interface position prior to the experiments with values varying between 0.2 K/mm and 2.9 K/mm. Both liquids showed a qualitatively similar reorientation behavior. The reorientation characteristics were found to depend on the value of the applied gradient and on the material properties of the experimental liquids. Numerical simulation showed a good qualitative agreement with a previous experiment with 1.34 K/mm using liquid argon, demonstrating main characteristic features of the experiment.

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 next-generation launchers. After the end of thrust of the engines the propellant is driven by the now dominating capillary forces from the equilibrium position under normal gravity to a new equilibrium position under microgravity. Until the new equilibrium position is reached, the interface exhibits decaying damped oscillations typical of underdamped systems and the whole process is known as free surface or interface reorientation (Fig. 1). 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 goal of the presented experimental and supporting numerical study is the investigation of the influence of non-isothermal boundary conditions, adjacent to the ullage a superheated wall in comparison to the liquid, on the reorientation of sub-cooled, single-component and two-phase systems of a cryogenic liquid and its vapor. The process of evaporation (and condensation) of the cryogenic liquid after a step reduction in gravity and the influence on the apparent or the dynamic contact angle γ_d between the interface and the wall (Fig. 1) are assumed to be the main effects.

The first experiments on the behavior of a liquid–vapor interface of cryogenic liquids after a step reduction of gravity were performed by Siegert et al. [22]. Cylinders with inside diameters of 5.8 cm and 8.3 cm and spherical containers with 50% fill ratio with inside diameters of 8.3 cm and 12.4 cm were used for the experiments with liquid nitrogen. The purity of the experimental liquid was specified as 99.99% (military specification P-27401A). Only one experiment with liquid hydrogen with a spherical container and 80% fill ratio with an inside diameter of 8.3 cm was performed. The liquid purity was specified as 99.995% (military specification P-27201). The subject of the investigation was the new equilibrium interface under microgravity. A determination of the time required for the liquid–vapor interface to reach the microgravity equilibrium position was proposed. This time was defined as the time for the first pass of the interface through its equilibrium position as a result of the limited μg experiment time, insufficient for the complete decay of the interface oscillations. Also provisions were made to reduce the heat inputs to the experiment tanks in order to minimize any effect of heat addition on the behavior of the

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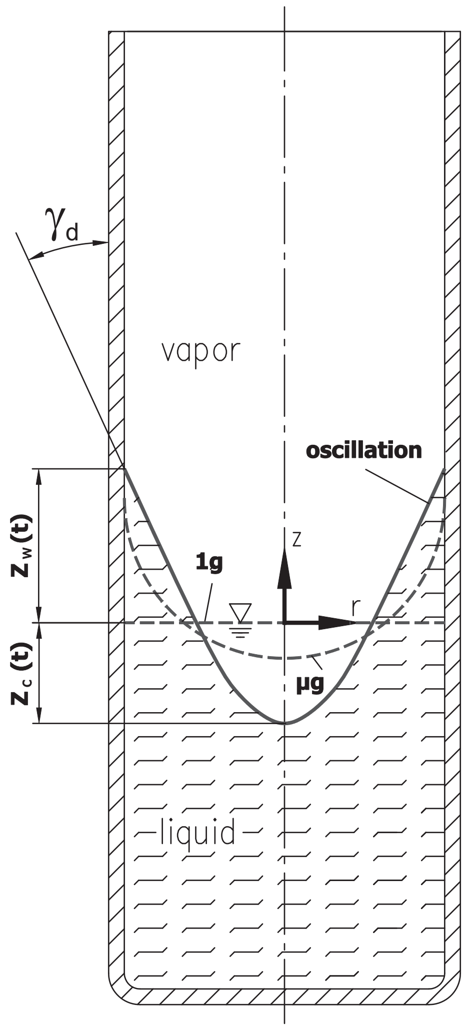

Fig. 1. Sketch of a generic experimental cell for the investigation of the reorientation with characteristic values of the oscillation, the contact line coordinate on the wall Z_w and the center coordinate Z_c. The angle between the interface and the wall at the position of the contact line is the dynamic contact angle γ_d.

liquid during the μg phase. Thus considering the flight time of 2.2 s, additional sources can be neglected.

The earliest investigations on the total reorientation time and one characteristic of the interface oscillations, the motion of its center point $Z_c(t)$ as depicted in Fig. 1, of a liquid after a step reduction of gravity were performed by Weislogel and Ross [25]. The experiments were performed with storable liquids in cylindrical geometries under isothermal conditions varying the kinematic viscosity ν and the static contact angle γ_s of the liquid in wide ranges. Michaelis et al. [20] performed further isothermal experiments with storable liquids under isothermal conditions in cylindrical geometries with different values of the OHNESORGE number, defined as $Oh = \sqrt{\nu^2\rho/\sigma R}$ where ν is the kinematic viscosity of the liquid (defined as $\nu = \mu/\rho$ with μ the dynamic viscosity), ρ – the density of the liquid, σ – the surface tension of the liquid, and R is the radius of the cylinder. The static contact angle was varied in the range $0^\circ \leqslant \gamma_s \leqslant 62^\circ$. This was the first investigation of the motion of the contact line $Z_w(t)$ (Fig. 1) and the relation between the motions of $Z_c(t)$ and $Z_w(t)$ depending on the values of OHNESORGE and $\gamma_s = 0$. For small values of the OHNESORGE number $Oh \leqslant 2 \cdot 10^{-3}$ and low values of the static contact angle $\gamma_s < 10^\circ$ both motions are essentially decoupled, meaning that the center point exhibits its damped oscillation while the contact line remains motionless after the maximum deflection. A macroscopic liquid layer was formed at the wall which underwent drainage during the interface oscillations. Gerstmann et al. [9] performed experiments on the interface reorientation in cylindrical geometries under non-isothermal conditions. They used storable and completely wettable liquids ($\gamma_s = 0$) for the low values of the OHNESORGE number. A definite temperature difference was applied between the liquid and the wall above the interface. The volume above the interface was occupied by the vapor and a non-condensable gas, allowing for thermo-capillary convection in the liquid. The formation of the liquid layer on the wall was prevented due to an enlargement of the dynamic contact angle as a consequence of thermo-capillary convection. The contact line exhibited an oscillating motion. The frequency of the center point followed the behavior of the contact line. The frequency increased with increase of the temperature difference between liquid and wall.

Stief et al. [23] performed experimental investigations on the liquid–vapor behavior of a cryogenic liquid ($\gamma_s = 0$) in a cylindrical geometry with an inside diameter of 5.1 cm after a step reduction of gravity under isothermal conditions. Liquid nitrogen was used as an experimental liquid. A macroscopic liquid layer was observed on the cylinder wall. Only a uni-directional motion of the contact line could be observed (no receding or oscillation). Kulev and Dreyer [18] investigated the reorientation of liquid argon under non-isothermal conditions in the same cylindrical geometry as Stief et al. [23]. An axial wall temperature gradient between 0.15 K/mm and 1.93 K/mm was applied above the interface prior to the step reduction of gravity. No liquid layer was observed on the cylinder wall. A general dependence on the value of the wall temperature gradient was observed. A transition of the contact line behavior was observed – from an aperiodic motion through a receding to an oscillatory motion. Both the oscillation of the interface center point and the pressure increase of the vapor followed the contact line behavior. Thus the frequency of the center point increased with the increase of the wall temperature gradient. The pressure increase was greater for greater values of the gradients. The pressure rate exhibited peak values correlated to the receding motion of the contact line for the larger gradient values.

As already mentioned, the dynamic contact angle can be varied through the mechanism of thermo-capillary convection which can be observed in two-species systems. The mechanism is based on the presence of a temperature difference between the wall and the liquid and on the temperature dependence (decrease for most liquids) of the surface tension. Thus the convection arises due to the transport of liquid from the warmer region with lower surface tension (near the contact line due to the heat flux from the wall) towards the inner colder interface region with a higher surface tension. The dynamic contact angle is increased through the increase of the temperature difference, Anderson and Davis [2]. Thermo-capillary convection should not occur in a single-species system because it is assumed that the interface always is at the saturation temperature. There are two other mechanisms which vary the dynamic contact angle by an applied temperature difference between the liquid and the wall. The first one is the so-called vapor recoil as observed by Anderson and Davis [2]. By this mechanism the pressure on the interface is increased by the momentum transfer from the escaping liquid particles into the vapor by the evaporation. The mass transfer is highest at the contact line because of the maximum of the evaporation rate there (greatest temperature difference between wall and liquid). The pressure increase is consequently highest in this region. This non-uniform pressure distribution increases the contact angle. The second mechanism is the evaporation/condensation process at the liquid–vapor interface. Anderson and Davis [2] investigated the evaporation process macroscopically neglecting gravity. They found that the effects which tend to increase the contact angle, promote the evaporation in