# Axial Sloshing of Liquid Hydrogen at low Bond Numbers with Superheated Walls

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The dynamic behavior of liquids in moving containers with application to space technology, commonly known as sloshing, has been the focus of many studies since the early 60s. Collections and textbooks are dedicated to this topic ([Abraham 1966, Dodge 2000, Ibrahim 2005]). Sloshing is characterized by the ratio of the hydrostatic pressure due to a characteristic acceleration $a_\mathrm{C}$, and the capillary pressure. This ratio is commonly known as the Bond number (or Eötvös number)

$$\mathrm{Bo} = \frac{\rho_\mathrm{L} a_\mathrm{C} R^2}{\sigma} \tag{1}$$

The density of the liquid $\rho_\mathrm{L}$ times the acceleration $a_\mathrm{C}$ times a characteristic length, typically the radius $R$ of a container, yields the hydrostatic pressure, whereas the surface tension $\sigma$ divided by $R$ gives the capillary pressure. Even though the lengths scale for the hydrostatic pressure and the capillary pressure are not the same, usually one scale is used in literature. High Bond number sloshing occurs in the propelled phase of a spacecraft. Theories are available, and testing can be performed at Earth's gravity using sloshing tables. Results are being used to validate and tune the codes, which are used by aerospace industries for the design of liquid filled containers.

Low Bond number sloshing, in particular with perfectly wetting liquids (storable and cryogenic propellants are usually wetting the metallic containers wall), requires a relevant test environment, such as compensated gravity or neutral buoyancy. Theoretical analyses are limited to small surface amplitudes and larger contact angles.

Future launcher concepts use liquid hydrogen (LH2) or liquid methane (CH4) as propellant and liquid oxygen (LOX) as oxidizer. They may experience long ballistic phases with varying acceleration levels. For propellant management purposes, it is important to understand the response of cryogenic fluids (liquid and gas) to these disturbances. Furthermore, superheated tank walls influence the motion of free surfaces, and may cause evaporation and pressure changes. This study investigates the free surface reorientation of liquid hydrogen upon a sudden step reduction of gravity in presence of a superheated wall. The pressure was set around normal pressure leading to a saturation temperature of 20 Kelvin. This test case can be used to validate numerical codes which solve the mass, momentum and energy conservation equations including the thermal behavior of the walls.

The experiment consists of a glass cylinder partly filled with liquid hydrogen enclosed in a cryostat to insulate it from ambient conditions. Temperatures were recorded at several locations along the cylinder and in the gas phase. The pressure inside the cylinder was recorded with a pressure transducer and optical access was enabled with an endoscope. Various heating elements were glued to the cylinder for thermal control of the experiment. Thermal stratification in the liquid phase could be neutralized and wall heating elements were used to establish a wall temperature gradient in vertical direction.

Experiments were carried out in the drop tower at the University of Bremen. Experiment time in microgravity lasted five seconds. Several experiments with varying wall temperature gradients were performed. The reorientation of the free surface could be recorded focusing on wall and center point locations. A final equilibrium surface position could not be achieved due to limited experiment time.

The paper will review previous results with liquid

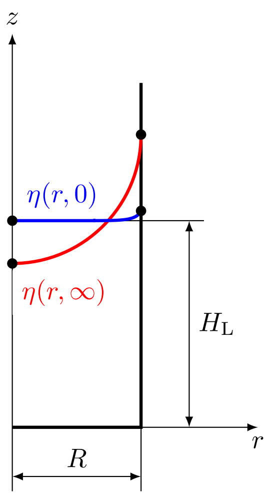


Figure 1: Initial $\eta(r, 0)$ and final $\eta(r, \infty)$ interface contour. The container is initially filled up to a height $H_{\mathrm{L}}$.

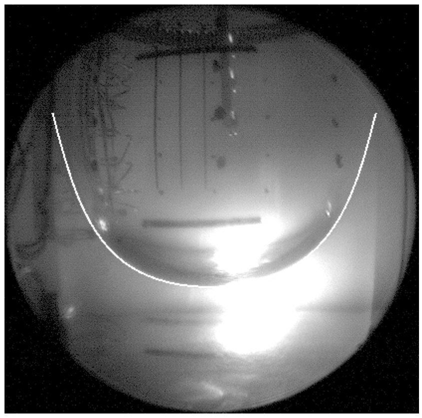

Figure 2: Intermediate surface contour of liquid hydrogen in a gaseous hydrogen environment. The free surface is highlighted in white. The static contact angle is zero but the tangent at the wall is not visible due to optical distortions of the cylindrical container wall.

argon and methane ([Kulev et al. 2014]) and liquid hydrogen ([Schmitt and Dreyer 2015]), and present new results ([Friese et al. 2019]). In addition, different numerical codes have been used to get the free surface position, the wall heat transfer, the evaporated mass, and the pressure progression. The results contribute to the understanding of the behavior of cryogenic liquids, such as hydrogen, oxygen, and methane, in launchers, spacecrafts and future orbital propellant depots.

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