Non-Isothermal sloshing for space applications: from a ground-based experimental characterisation to microgravity conditions

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Introduction

Liquid cryogenic propellants are at the forefront of space propulsion due to their optimal trade-off between performance and weight (Sutton et al. 2017). As a result, investigations on the sloshing dynamics of such fuels have been carried out since the early 1960s. Sloshing, defined as the movement of the free liquid surface within a reservoir (Abramson, 1966), induces two types of undesirable effects: (a) displacement of fuel tank's centre of mass, which disturbs the stability and manoeuvrability of the spacecraft; (b) thermal mixing between the pressurised ullage and subcooled liquid, which can generate large fluctuations in the tank pressure, leading to structural instabilities and thrust oscillations in the propulsive system.

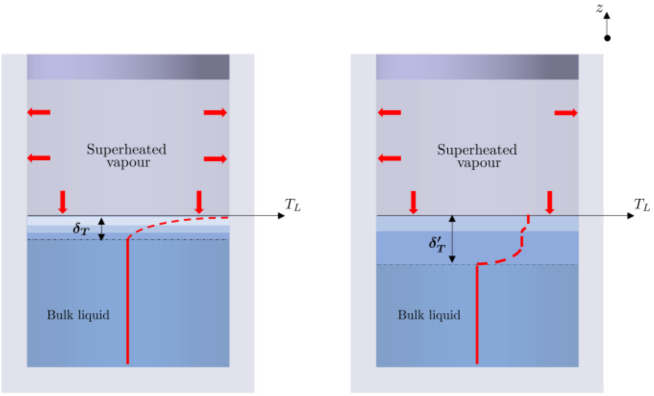
Prior to launch, the propellant tanks are pressurised according to the optimal operating conditions for the propellant feed system. If the holding time is large enough, a vertical thermal stratification develops in the liquid due to natural convection and conduction. As depicted in Figure 1a, the liquid's thermal field features a warmer region extending from the interface until a depth δ_T, and a subcooled region defined by a quasi-homogeneous condition. If dynamic perturbations (e.g., booster separation or aerodynamic forces) induce liquid sloshing, the warmer liquid in the thermal boundary layer mixes with the subcooled liquid from the bulk, lowering the temperature at the free surface. The de-stratification (depicted in Figure 1b) results in the cooling of the ullage gas, hence condensation and consequently a pressure drop in the tank. The magnitude of this pressure drop depends on (a) the sloshing regime, (b) the pressurisation technique, (c) the pressurant type and (d) the ullage volume (Arndt, 2012; Foreest, 2014).

The present research aims to develop a reduced-scale experiment using non-cryogenic replacement fluids to characterise the heat and mass transfer between the liquid and the gas due to sloshing-induced mixing.

The research questions we seek to answer are:

1. What is the impact of different initial non-isothermal sloshing conditions (e.g., tank pressure, ullage temperature and thermal boundary layer thickness) on the thermodynamic evolution of the system under lateral sloshing conditions?

2. What is the sloshing excitation condition's impact on the thermodynamic evolution of the system?



(a) (b)

Figure 1: Schematic representation of the evolution of vertical temperature profiles and the thickness of thermal boundary layers in the liquid's uppermost region adapted from Lacapere et al. (2009): (a) thermal profile before sloshing initialisation; (b) thermal profile after sloshing induced mixing.

The developed small-scale experiment for ground-based characterisation represents the first iteration for the experimental campaign under reduced gravity conditions, which will take place next year on the 80th ESA Parabolic Flight. This presentation reports on the lessons learned and the refinements that will be considered for the campaign in microgravity.

Preliminary experimental setup

The experimental setup, represented in Figure 2, has been designed to study lateral sloshing for different non-isothermal conditions resorting to non-cryogenic fluids, such as HFE-7200 and HFE-7000. The setup comprises a quartz sloshing cell, an external reservoir, and a connecting pressure line with several valves.

The sloshing cell is a quartz rectangular cuboid, allowing non-intrusive optical measurement techniques (Simonini et al. 2021), with a radius $R_S = 40$ mm, and a total height $H_S = 120$ mm. It is instrumented with thermocouples across the ullage and liquid to analyse the thermal evolution of the system, as well as a pressure transducer mounted on the top cover to monitor pressure fluctuations. An active pressurisation system is employed by resorting to an external reservoir with heating capabilities and a total volume V_R = 2.4 L. A thermocouple connected to a PID controller and a pressure transducer are used to impose the desired superheated vapour conditions in this reservoir. The quartz cell is connected to this external reservoir via the pressure line shown in Figure 2.

To avoid impingement of the vapour jet on the liquid surface, the vapour is injected through a diffuser at the sloshing cell top cover. Additionally, this pressure-driven system is controlled through a ball valve and a swing-check valve. A pressure regulator and transducer are also built into the line, ensuring operational safety. Both tanks have a port that allows a vacuum pump connection to ensure a single species system by extracting the air. A graded filling bottle is connected, through the same port, ensuring an accurate filling of the sloshing cell and reservoir.

The experimental setup is mounted on the SHAKESPEARE (SHaking Aparatus for Kinetic Experiments of Sloshing Projects with EArthquake Reproduction) shaking table with three sliding modules at the von Karman Institute. Here the setup will be laterally excited in the *x*-direction.

Figure 2: Experimental setup composed of quartz sloshing cell (clear blue), heating reservoir (grey and white), connecting pipeline (light grey) and vacuum and filling port (blue).

With the vision set in future iterations for the parabolic flight test campaign, the following high-level requirements for the experimental setup were employed to drive the design: (a) compact setup, quick to assemble and disassemble; (b) rapid initialisation, restricted to under five minutes; (c) redundant measures must be employed to meet safety constraints; (d) optical measurement techniques capability.

Expected results and facility outcomes

Initially, it is critical to perform pressurisation tests in which an initial condition for the reservoir's superheated vapour and sloshing cell ullage is fixed. Hereafter, resorting to the employed instrumentation, the objectives are the following: (a) evaluate the thermal boundary layer thickness for a pressurisation cycle; (b) quantify the heat rate transfer between the pressurant vapour, the liquid and walls; (c) evaluate the sloshing cell pressurisation time; (d) determine the number of pressurisation cycles for an initial vapour mass in the external reservoir.

Once the initialisation procedure is well understood, the non-isothermal sloshing experiments will consider different excitation amplitudes and frequencies to generate wave dynamics from the three main wave regimes: planar, chaotic and swirl waves (Miles, 1984). Temperature and pressure evolutions will be extracted, reconstructing the vertical temperature profiles, and characterising the sloshing-induced thermal mixing and the characteristic pressure drop.

Regarding the facility operational learning outcomes, the prominent question marks to be answered settle on: (a) the number of pressurisation cycles attainable for an initial reservoir condition; (b) pressure tightness across the system; (c) compatibility between the system components and working fluid. The presentation will illustrate how the results on-ground will be translated into an improved design for the parabolic flight campaign.

Conclusions

The present work aims to develop an experiment to characterise non-isothermal sloshing. The outcomes from this campaign will set an experimental database to allow future development and calibration of simplified models capable of predicting the pressure and temperature evolutions during sloshing excitations. In the extended version of this work, the experience acquainted through the operation of the designed facility will determine how to proceed further with the architecture of the next VKI (von Karman Institute) microgravity experimental campaign taking place next year on board the 80th ESA Parabolic Flight. The described experimental setup and respective test campaign is expected to occur at VKI between July and August 2022.

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