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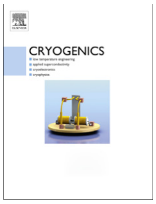

Free surface oscillations of liquid hydrogen in microgravity conditions

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ABSTRACT

Experiments were performed to investigate the reorientation behavior and axial sloshing of liquid parahydrogen in a partly filled right circular cylinder due to a step reduction of gravity. Different temperature gradients along the cylinder wall in vertical direction were imposed to examine the influence of a wall superheat on the free surface. Experiments were conducted in the drop tower at the University of Bremen which provides a microgravity time of 4.7 s and a compensated gravity environment of 10^{-6} g_0 (acceleration due to gravity). The thermal preparation of the experiments allowed to create defined wall temperature gradients and a stratified or homogenous liquid temperature distribution. Several sensors along the cylinder wall and in the vapor region monitored the temperature. The pressure inside the experiment was recorded and visual access was enabled by an endoscope. The experiments showed that the wall superheat has an influence on the free surface as well as on the temperature and pressure evolutions.

1. Introduction

Cryogenic fluid management with variable accelerations becomes more important since new launcher concepts require a liquid hydrogen/oxygen upper stage with restart capability. For save operation it is crucial to understand the complex system of a cryogenic fluid with a free surface in presence of a superheated tank wall. A step reduction of the acceleration occurs when the spacecraft enters the ballistic flight phase after shut down of the engines. At this instance of time hydrostatic forces vanish with the sudden absence of body forces. The free surface shape changes from a flat shape to a shape with constant curvature and undergoes a damped axial sloshing motion. This reorientation process is idealized for right circular cylinders and may differ from rocket stages after engine cut off.

Siegert et al. [20] investigated the free surface behavior of a free surface in a cylinder and a sphere upon step reduction of gravity. Microgravity lasted for 2.25 s. The working fluids were ethyl alcohol, carbon tetrachloride and a water ethyl alcohol mixture. The primary objective was to observe the time needed for the free surface to reach a new equilibrium. It could be shown that the reorientation is driven by capillary and inertial forces, and that the Weber number We can be used for scaling. Michaelis et al. [14] focused on the first capillary rise of a free surface in a cylindrical tank. The experimental fluids were a series of silicone oils. Two geometries with different radii were chosen. The static contact angle varied between 2° and 60°. It was determined that the initial contact line rise is dependent on the Morton number Mo and the static contact angle. Weislogel et al. [22] studied the reorientation time and their dependency on contact angle and kinematic viscosity. A number of liquids, varying contact angles and cylinder diameters were combined to perform a scale analysis.

First weightlessness experiments with a partly filled sphere with liquid hydrogen were performed with four Aerobee sounding rocket experiments [6,11,15,18]. The first two experiments had a uniform heat source present whereas the third and fourth flight investigated the influence of a non uniform heat source. Primary objects were to investigate the free surface under microgravity conditions and observe heat transfer between container wall and fluid. The experiments showed that stratification occurred resulting in a higher surface than bulk temperature. The advancing liquid along the superheated tank wall showed behavior of subcooled nucleate boiling. The first three experiments faced problems with telemetry, data recovery or microgravity quality. The fourth flight could establish a sufficient environment for 3.5 min. Liquid hydrogen filled up 25.1% of the container volume at lift off. In microgravity, temperature sensors indicated fully wetted walls which dried out due to the wall superheat. Nucleate boiling as well as bubble formation could be observed.

First drop tower experiments with cryogenic nitrogen and hydrogen were performed by Siegert et al. [21]. The test liquids showed a perfectly wetting behavior with glass tank walls. The

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Nomenclature

Latin letters

Variable	Description, dimension
A	area, m^2
a	thermal diffusivity, $m^2\,s^{-1}$
c_p	specific heat at constant pressure, $J\,kg^{-1}\,K^{-1}$
c_v	specific heat at constant volume, $J\,kg^{-1}\,K^{-1}$
D	outer diameter, m
d	inner diameter, m
f	frequency, s^{-1}
g	acceleration, gravity, $m\,s^{-2}$
h	height, m
Δh	heat of evaporation, $J\,kg^{-1}$
L	characteristic length, m
m	mass, kg
n	refractive index, –
p	pressure, Pa
r	axial direction, coordinate system, m
R	radius, m
T	temperature, K
T	periodic time, s
t	time, s
u	velocity, $m\,s^{-1}$
V	volume, m^3
z	vertical direction, coordinate system, m

Greek letters

Variable	Description, dimension
γ	contact angle, °
λ	heat conductivity, $W\,m^{-1}\,K^{-1}$
λ	wavelength, nm
μ	liquid dynamic viscosity, Pa s
ν	liquid kinematic viscosity, $m^2\,s^{-1}$
ρ	liquid density, $kg\,m^{-3}$
σ	surface tension, $N\,m^{-1}$
ω	frequency, s^{-1}

Dimensionless numbers

Variable	Name, formulation
Bo	Bond number, $\frac{\rho g L^2}{\sigma}$
Mo	Morton number, $\left(\frac{g\mu^4}{\rho\sigma^3}\right)^{1/4}$
Oh	Ohnesorge number, $\left(\frac{\rho\nu^2}{\sigma R}\right)^{1/2}$
We	Weber number, $\frac{\rho L u^2}{\sigma}$

Subscripts

Name	Description
0	initial conditions
1	final conditions
1	first
2	second
3	third
a	ambient
b	bottom
b	back
BH	bottom heater
bs	borosilicate
c	center
c	capillary
e	experiment
ec	experiment cylinder
f	front
FH	flange heater
GH	glass heater
h	parahydrogen
he	helium
l	liquid
max	maximum
min	minimum
n	numerical operator
p	scaling based on pressure
s	static
sat	saturation conditions
sub	subcooling
sup	superheated
t	theory
u	scaling based on convection and acceleration forces
v	vapor
$v1$	vapor
$v2$	vapor
$v3$	vapor
w	wall
wif	glass cylinder wall, free surface
$wl1$	glass cylinder wall, liquid
$wl2$	glass cylinder wall, liquid
$wv1$	glass cylinder wall, vapor
$wv2$	glass cylinder wall, vapor
$wv3$	glass cylinder wall, vapor
$wv4$	glass cylinder wall, vapor
$wv5$	glass cylinder wall, vapor

Superscript

Name	Description
$*$	dimensionless form

hydrogen tests were conducted with spherical containers only. Furthermore, these experiments helped to extend the Weber number criterion for cryogenic liquids. Kulev and Dreyer [8] and Kulev et al. [7] investigated the influence of a wall temperature gradient on the reorientation of cryogenic fluids. Test liquids were argon and methane in the presence of varying wall temperature gradients. Both fluids responded similarly to the superheated wall. Apparent contact angle and oscillation frequency of the center point increased with the applied wall superheat. Furthermore, they showed that the pressure progression corresponded to the contact line movement, which led to the assumption that the pressure is driven by evaporation of the advancing liquid layer. Numerical simulations supported the experimental results.

Theoretical and experimental investigations were conducted to scale the free surface shape and its behavior to varying acceleration levels. Concus [2] showed that a stable free surface shape is mainly influenced by gravity acceleration g and surface tension σ, and is scaled with the Bond number

$$\mathrm{Bo} = \frac{\rho g L^2}{\sigma} \tag{1}$$

The Bond number compares the hydrostatic pressure with the capillary pressure. For a cylindrical container with a circular free surface the tank radius R is used for the characteristic length L. For high Bond numbers ($\mathrm{Bo} \gg 1$) gravity is the dominating force which results in a flat surface. The free surface meets the wall under a certain static contact angle γ_s depending on the surface energies.