



Pressure variations in a cryogenic liquid storage tank subjected to periodic excitations



C. Ludwig^a, M.E. Dreyer^{b,*}, E.J. Hopfinger^c

^aDLR, German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen, Germany

^bZARM, University of Bremen, 28359 Bremen, Germany

^cLEGI/CNRS/UJF, B.P. 53, 38041 Grenoble, France

ARTICLE INFO

Article history:

Received 30 November 2012

Received in revised form 4 June 2013

Accepted 29 June 2013

Available online 2 August 2013

Keywords:

Sloshing

Cryogenics

Pressure drop

Propellant tanks

Launcher upper stages

ABSTRACT

The pressure change in a partially filled liquid nitrogen tank, subjected to periodic lateral forces, has been investigated experimentally. The cylindrical tank has a radius of $R = 0.148$ m and is filled up to 69% of the total volume (43×10^{-3} m³). Six different sloshing conditions were considered, with the wave amplitude b of the first asymmetric mode ranging from $b/R = 0.12$ up to wave breaking conditions of $b/R \geq 0.54$. The tank was pressurized with nitrogen vapor and the pressure at sloshing initiation was in general $p_i \approx 250$ kPa. Pressure drops in the order of 100 kPa have been measured and the dependency of these pressure drops on wave amplitude has been determined. The integrated temperature sensors allowed to measure the vapor temperature change and, with a high resolution, the thermal boundary layer in the liquid. The effective diffusion coefficient model of Das and Hopfinger (2009) [2] has been extended and allows calculating the temperature distribution in the thermal boundary layer, as well as the pressure drop as a function of the effective diffusion coefficient. A novel result is that the calculated temperature distribution in the thermal boundary layer deviates from the measured one, relating to a stop in the pressure drop. The sloshing Nusselt number $Nu_s = D_e/D_0$ is shown to correlate well with a Reynolds number that contains the wave amplitude.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

In cryogenic propellant tanks of rockets, as well as in other liquefied gas storage tanks, large pressure changes can occur due to condensation or evaporation at the liquid–vapor interface. These pressure changes, and especially the rate of pressure change, can be considerably enhanced when the tank is subjected to excitations in a way that the liquid vapor interface is sloshing. It is of great practical and fundamental interest to be able to relate the pressure change to the sloshing conditions. Moran et al. [1] showed that in a partially filled liquid hydrogen (LH2) tank, pressurized to 250 kPa, a pressure change (pressure drop) of about 100 kPa can occur in less than 10 s. Das and Hopfinger [2] and Hopfinger and Das [3] conducted experiments with volatile liquids, storable at room temperature, aimed at understanding the physical processes and the dependency of the pressure change on the physical properties of the liquid and sloshing conditions. A condensation–evaporation model has been developed by them, giving the rate of pressure change as a function of the physical properties of the

liquid (expressed by the Jakob number), the temperature gradient near the liquid–vapor interface, and an effective thermal diffusivity depending on the sloshing conditions. This effective thermal diffusivity coefficient can be two orders of magnitudes larger than the molecular thermal diffusivity [2]. Arndt [4] showed that, as expected, the presence of a non-condensable gas decreases condensation and increases evaporation. The latter experiments were limited to constant sloshing conditions. Das and Hopfinger [2] used only axial excitations and storable liquids with different pressurization conditions. For a better understanding of the relation between the pressure drop and the sloshing conditions of cryogenic liquids, further experiments and analysis were clearly needed. The experiments, presented in this paper have been conducted with liquid nitrogen (LN2) for identical initial thermodynamic conditions but different sloshing conditions. These experiments were aimed at establishing a Nusselt number dependency on sloshing conditions. Special attention was given to adequately resolving the thermal boundary layer in the liquid. In the next section, an extended form of the mass transfer model of Das and Hopfinger [2] is presented, containing the thermal boundary layer development. The experimental setup and procedures are discussed in Section 3, together with a detailed presentation of the sloshing conditions with the measured and evaluated wave amplitudes. Section 4 pre-

* Corresponding author. Tel.: +49 421 218-57866.

E-mail address: dreyer@zarm.uni-bremen.de (M.E. Dreyer).

Nomenclature

Roman letters

| | |
|--------------|---|
| A_f | forcing amplitude |
| B, B_1 | prefactors |
| b | wave amplitude |
| C | constant or coefficient in (8) |
| c_p | specific heat capacity |
| D_0 | liquid thermal diffusivity |
| D_e | effective thermal diffusivity |
| d | tank wall thickness |
| f | frequency |
| f_1 | natural frequency |
| H_l | liquid height |
| H_v | vapor height |
| Δh_v | latent heat of evaporation/condensation |
| K | constant of order 1 |
| m | mass |
| p | pressure |
| Q | heat flux |
| q | heat flux per unit area |
| r | radial coordinate |
| R | tank radius |
| R_s | specific gas constant |
| S | free surface area |
| S_A | cross-sectional wall area |
| S_e | evaporation surface |
| T | temperature |
| \bar{T}_v | mean vapor temperature |
| T_w | wall temperature |
| T_ω | oscillation period, $T_\omega = 1/f$ |
| t | time |
| t_d | decay time after sloshing end |
| U_j | liquid velocity field |
| V | volume |
| w | velocity in z direction |
| w_e | evaporation velocity |
| w_c | condensation velocity |
| z | vertical coordinate |

Greek letters

| | |
|-----------|--|
| β_i | bifurcation parameters of Miles [9] with $i = 2, 3, 4$ |
| γ | amplitude–radius ratio |

| | |
|-----------------|---|
| δ | damping coefficient |
| δ_M | mixing thickness |
| δ_T | thermal boundary layer thickness |
| $\delta_{T,g}$ | thermal boundary layer gradient thickness |
| ε_1 | eigenvalue of first asymmetric mode |
| η_1 | frequency ratio |
| Θ | characteristic temperature difference |
| λ | thermal conductivity |
| μ | dynamic viscosity |
| ν | kinematic viscosity |
| ρ | density |
| ϕ | azimuthal coordinate |
| \mathcal{X} | damping rate |
| ω | angular wave frequency |
| ω_1 | natural angular wave frequency |

Subscripts

| | |
|----------|---|
| 0 | start |
| c | critical |
| exp | experiment |
| f | end |
| i | initial |
| j | coordinates $j = (r, \phi, z)$, z vertical |
| l | liquid |
| m | maximal |
| S | sloshing |
| s | saturation |
| u | ullage |
| v | vapor |
| w | wall |
| Γ | liquid surface |

Nondimensional numbers

| | |
|--|--------------------------|
| $Ga = \frac{gR^3}{\nu^2}$ | Galilei number |
| $Ja = \frac{\rho_l c_{p,l} \Theta}{\rho_{v,s} \Delta h_v}$ | Jacob number |
| $Nu_S = \frac{D_e}{D_0}$ | sloshing Nusselt number |
| $Pr = \frac{c_p \mu}{\lambda}$ | Prandtl number |
| $Re_S = \frac{\omega b^2}{\nu}$ | sloshing Reynolds number |

sents the experimental results of the pressure drops as well as the thermal boundary layer development, including a comparison to a theoretical model. From the measured pressure drops, the values of the effective diffusion have been determined. The sloshing Nusselt number Nu_S is presented in Section 5 as a function of a sloshing Reynolds number Re_S . In Section 6, the conclusions drawn from this study are presented.

2. Interfacial mass transfer model

When the liquid surface (the liquid–vapor or gas interface) is motionless, the mass transfer depends on the thermodynamic conditions at the interface. We assume that the mass flux is related to the heat flux in the liquid. Additionally, it is assumed that the heat flux in the vapor is at least one order of magnitude lower and is therefore negligible. When the liquid is sloshing, the mass transfer is increased and Hopfinger and Das [3] and Das and Hopfinger [2] proposed to express this increased mass transfer by an effective diffusion coefficient. This effective diffusion coefficient with respect to the thermal diffusivity is a Nusselt number, that depends

on the sloshing conditions. For capillary waves, such a Nusselt number has been proposed by Hopfinger and Das [3] as a function of the wave amplitude. However, for gravity wave sloshing this was not possible mainly because of the lack of adequate experimental data.

The thermal energy flux equation is

$$\rho_l c_{p,l} \left(\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j} T U_j \right) = \rho_l c_{p,l} D_0 \frac{\partial^2 T}{\partial z^2} \quad (1)$$

with the liquid density ρ_l , the specific heat capacity of the liquid $c_{p,l}$, the temperature T , the liquid velocity field U_j and the liquid's thermal diffusivity D_0 . Incompressibility conditions were used. It is possible to decompose temperature and liquid velocity into a mean and fluctuating part, i.e. $T = \bar{T} + T'$ and $U_j = \bar{U}_j + U'_j$. In cylindrical coordinates, the index j is defined as $j = (r, \phi, z)$, where z is vertical, r radial and ϕ azimuthal, measured from the direction of container excitation $x = (r, \phi = 0)$ (see Fig. 1).

By setting the mean velocity field $\bar{U}_j = 0$ and time averaging over a few oscillation periods, eliminating horizontal gradients (i.e. in r and ϕ direction), we can write

Download English Version:

<https://daneshyari.com/en/article/7057960>

Download Persian Version:

<https://daneshyari.com/article/7057960>

[Daneshyari.com](https://daneshyari.com)