Slosh to Swirl Transition

In Diffuse Interface Large Amplitude Motion

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ABSTRACT

We performed a numerical simulation of the sloshing of a diffusion interface between two miscible liquids (pure and salt water) in order to address the first step in the understanding of the behavior of very expandable cryogenic liquids. The two phases of some tenth of cm high are contained in a cylindrical container of 1 m in diameter in a gravitational stable configuration. Two ways of exciting internal waves are considered, by moving periodically the tank along one fixed direction and by moving up and down an insert located inside the tank. The study proves that the dynamic behavior of the miscible interface is quite different than that of a gas-liquid interface: when exciting the waves by periodic lateral motion, sheering-induced diffusion leads to a fast thickening of the interface and to a lowering of the first resonance mode of the tank which does not match at all with the experimental results; when exciting the internal wave by moving an insert, as in the experimental setup, the interface evolves by molecular diffusion only and the results are closer to the experimental one. Time series of the interface displacement are numerically obtained by solving the Navier-Stokes equation using the Phoenics numerical code. The existence of a swirling wave mode is confirmed; the transition threshold between sloshing and swirling is detected and the present result show discrepancies with the experiments.

INTRODUCTION

Understanding mechanisms of the sloshing of propellants in the tanks of space vehicles is an important issue both for the thermal control, pressure regulation and guidance. The problem has been studied experimentally in reduced scale experiments for equilibrium interfaces, e.g. between a gas and a liquid [1]. However, in the case of cryogenic, extremely expandable liquids, no real attempts have been made to address the dynamics of diffusion interfaces. These pseudo-interfaces correspond to the huge density gradient associated to heat diffusion interfaces in very expandable, low heat diffusing supercritical, or near-critical, van der Waals liquids. They can behave as real interfaces and give rise to Rayleigh-Taylor like instability [2]. The question of hyper compressible fluids modeling is extremely difficult since it needs the solution of van der Waals fluids equations which poses numerous numerical challenges [3]. Defining experiments on the dynamics of these interfaces is also extremely difficult because the fluid cells must be accurately thermostated and the setup confined in a Dewar. However experiments where recently performed on the dynamics of mass diffusion interfaces [4], which are of great interest for the above-mentioned goal. They addressed the transition from slosh to swirl of a diffusion interface between pure and salt water when the internal waves are resonantly forced by the vertical oscillations of an insert in a cylindrical container. They measured the time series of the interface displacement in different locations and the phase diagram of different points allowed to characterize the transition in terms of frequency and oscillation amplitude. However going beyond the interface displacement measurement is difficult and particularly difficult is the visualization of the flow pattern and other characteristics. We performed a numerical simulation of the sloshing of a diffusion interface in two configurations using the Phoenics code: interface forcing by lateral oscillatory motion of the container and interface forcing by vertical motion of an insert. Time series of the interface displacement are numerically obtained and the transition threshold is detected. The flow patterns are visualized and the results compared with the experiments whenever possible.

THE EXPERIMENTAL CONTEXT

The configuration under consideration is that of ref. [4]. A cylindrical container is filled with salt water and pure water in gravitationally stable configuration. The height of the fluid layers is 19 cm and the diameter of the cylinder is 1 m. The pure water is introduced first and then is introduced the salt water. The interface was resonantly forced by repeatedly moving an insert up and down (Fig. 1) at a frequency σ_f and amplitude A.

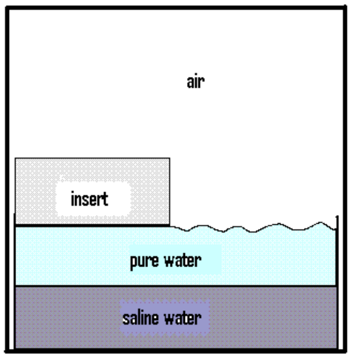


Figure 1: The experimental configuration: A cylindrical container of 1 m in diameter is partially filled with a two layer fluid in a gravitational stable position: a lower layer of salt water (0.19 m) and an upper layer of pure water (0.19 m). The insert is moved up and down to induce interface motion.

The shallow water dispersion relation for the primary mode in a circular domain is given by $\sigma_1 = k_1 c_0$, where $k_1 = 1.84/R$ where R is the basin radius and c_0 the linear phase speed [4, Lamb]. For a two-layer fluid, the phase speed can be approximated a $c_0^2 = g' h_E$, where g' is the reduced gravity defined by $g' = g\dfrac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$ and $h_E = \dfrac{h_1 h_2}{h_1 + h_2}$ the equivalent depth. For a typical experiment the periodic forcing is initiated at a prescribed frequency far from the frequency of the primary mode. The forcing frequency was then changed step by step, increasing or decreasing depending on the initial frequency value compared to the frequency of the primary mode, covering in each case the frequency range $0.75 \le \sigma_f \le 1.15$. For each value of the forcing frequency, the steady state was awaited to be reached after about 50 forcing periods when the free response is dissipated by interface and boundary friction. The interface displacement was collected by ultrasonic probes at different points along the sloshing radius of the interface and in the orthogonal (sloshing axes). In the absence of swirling, the interface motion on the latter is negligible whereas it takes a finite value when swirling appears. The experiments show a transition from slosh to swirl in the covered frequency range.

THE NUMERICAL CODE

We have modeled the above described systems using a cylindrical coordinate frame of reference and assuming a time dependent incompressible fluid. Cyclic boundary conditions are considered at 0 – 2π. We solved the equations of momentum, continuity and salt concentration, with the finite volume code Phoenics. The density variation in the body forces has been introduced through a Boussinesq approximation. The algorithm solution of the pressure field, which is essential for the determination of the velocity field, is obtained using the SIMPLEST algorithm based on the SIMPLER algorithm. The mesh size has been chosen in azimuthal direction (32 cells), in radial direction (20 cells) and in axial direction (60 cells). In azimuthal direction the grid is uniform and in the other direction it is finer at the salt interface. The grid is shown in Fig. 2 and is used to solve the insert motion-generated interface displacement; the lateral motion case grid is the same except that there is no insert and that the container is closed where the insert bottom is initially located.

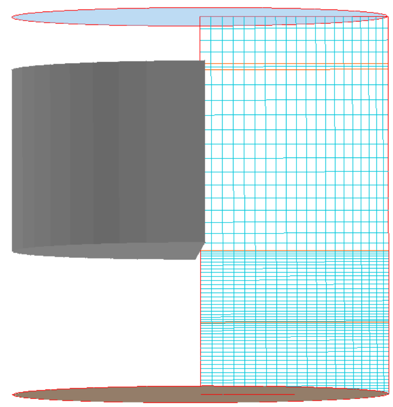


Figure 2: Mesh distribution in the Y-Z plane for the insert motion- induced interface motion.

The movement of the insert has been modeled with the special features of the Phoenics code: MOFOR (Moving Frames of Reference). The insert is moved with a sinusoidal oscillation: $a\sin(\omega t)$. In our cases, a = 0.015m and ω varies from 0.24 to 0.36 Hz.
In the case of the lateral oscillation acceleration in the form of $a\omega^2 \sin(\omega t)$ has been introduced as a body force term. The effect of such acceleration is directly dependent on the amplitude of the density gradient at the interface of salted and pure water whereas in the case of the insert the movement of the fluid depends only in the movement of the insert.

THE NUMERICAL SIMULATION

The values of the geometrical and mechanical parameters are those corresponding to run 6 in [4]

- Height of the salt water layer: 0.19 m
- Height of the pure water layer: 0.19 m

- $h_E = 0.095m$
- resonance frequency $\sigma_1 = 0.3128 Hz$
- Forcing frequency:

Set (1) $\sigma_f / \sigma_1 = 1.07, 0.96, 0.92, 0.78$ (decreasing)

Set (2) $\sigma_f / \sigma_1 = 0.80, 0.88, 0.92, 0.96$ (increasing)

- insert motion amplitude A= 0.015 m

The fluid is initially at rest and at thermodynamic equilibrium. At the initial time either by moving the whole tank or by moving the internal insert induces the motion of the interface. The collected data are the interface displacement time series at different measurement points (Fig.3) as well the interface displacement at probe 5 versus interface displacement at probe 1 for different values of the forcing frequency. The pure water is represented by a concentration value of zero and the salted water by a concentration value of one, following such definition the interface location has been chosen to be at a concentration value of 0.5. These data correspond to those measured in [4]. The numerical procedure is as close as that used during experiments: the lateral oscillation is maintained during 50 periods and the frequency is changed again increasingly or decreasingly. Each time period corresponds to 20s. The raw times series (non filtered) of the interface displacement containing the gravest mode as well as the higher harmonics are collected for the different decreasing frequencies and increasing frequency

For the present cases, we have not considered the free surface between the ambient air and the upper pure water layer which has raised convergence difficulties. This is why we considered the tank as a close volume entirely filled by the two fluid layers. In the continuation of this work, we are planning to account for such free surface in order to be more close to the experiments.

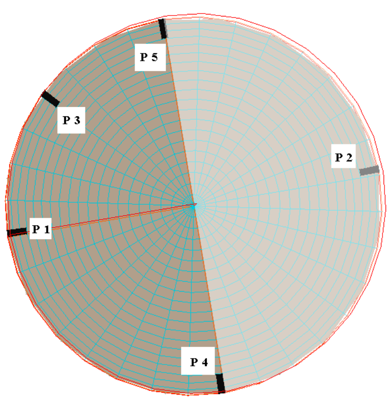


Figure 3: Location and numbering of the interface displacement probes.

Excitation of the primary mode by harmonic, linear motion of the tank

When studying equilibrium interface between two phases (liquid and gas for example) the mode of excitation of the sloshing modes in the tank can be achieved by two means: either a periodic translation of the tank or a vertical motion of an internal insert. This is why we first chose to force the interface motion by introducing a volumetric dragging inertia force corresponding to a periodic motion of the container at a prescribed frequency along a horizontal line. The amplitude of the container displacement was adjusted to produce interface motion amplitudes of the same order as those observed in experiments, namely 2m, the important thing being to detect the transition between slosh to swirl. We observe that the interface thickening is much faster than it would be by pure mass diffusion only as shown in Fig. 4. This due to the shear induced diffusion of the density interface.

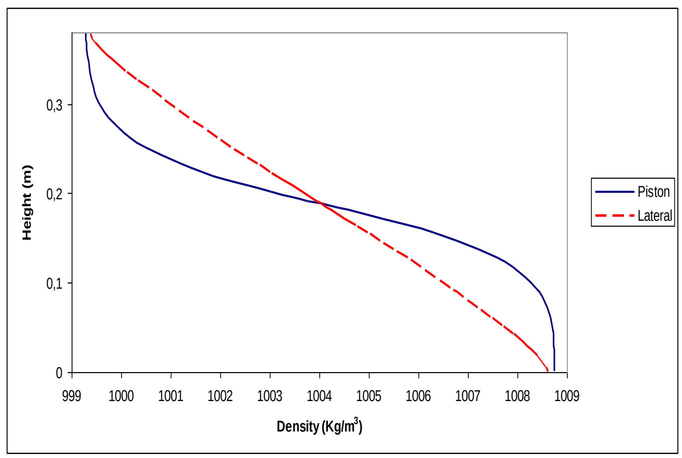


Figure. 4: Density profile for the case with a moving piston (solid) and for the case of lateral acceleration (dashed) after 100 periods: the thickening of the interface is due to shear –induced diffusion.

As a matter of facts, the inertia force only plays initially in the interface region (strong density gradient) and creates a shearing velocity field parallel to the latter. (Fig. 5) (in the absence of interface, there would be no motion generated in the closed container). The thickening of the interface provokes a decrease of the natural frequency of the container so that the forced response being detuned from the resonance conditions, the interface motion amplitude decreases which may explain the absence of transition to swirl.

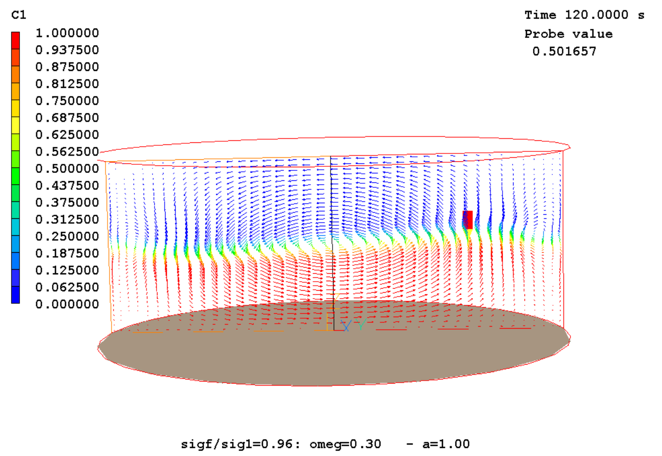


Figure. 5: Evidence of the shear flow induced in the vicinity of the interface by the oscillatory motion of the whole tank ($\sigma_f / \sigma_1 = 0.96$, decreasing frequencies).

The corresponding trajectories are given in Fig 7

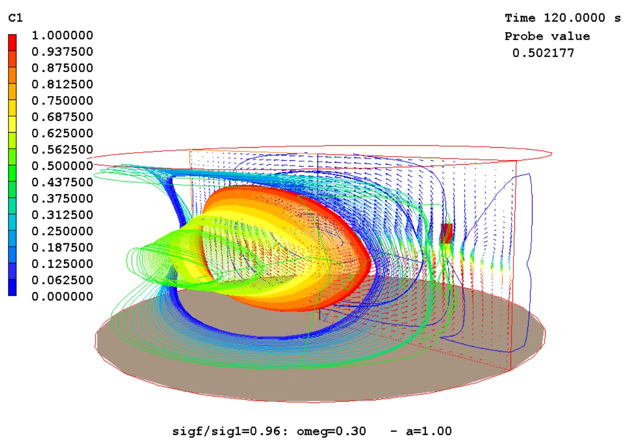


Figure 6: Trajectories of the fluid particles as the fluid moves under the tank lateral, harmonic motion

The result is that the swirl motion is never observed as shown in Fig. 7 for phase diagram.

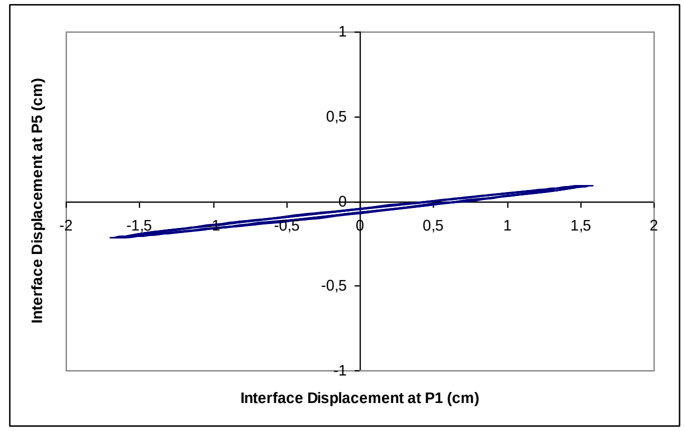


Figure 7: Interface motion at point 5 versus interface location at point 1 for $\sigma_f / \sigma_1 = 0.96$.

Excitation of the primary mode by moving an insert

Moving the tank to generate the interface motion is not appropriate since it provokes the interface shear-induced diffusion. We thus consider moving an insert inside the closed tank to avoid introducing a free surface. (Fig. 8) and to be however closer to the experimental configuration. The insert motion amplitude is set to 0.015 m as in [4]. For each value of the frequency of oscillations, 50 periods are computed in order to reach a steady state and to damp the free response of the container by boundary and bulk friction. Two sets of calculation are performed: one set of four calculations for decreasing frequencies: the first set for the decreasing frequencies such that:

$$\sigma_f / \sigma_1 = 1.07, 0.96, 0.92, 0.78$$

and one set for the following increasing frequencies

$$\sigma_f / \sigma_1 = 0.80, 0.88, 0.92, 0.96$$

The diffusion of the interface is closer to that produced by molecular diffusion only which means that the natural frequency does not vary much during the course of the experiment. The shear at the interface is much less (Fig. 8) since the origin of the motion is the surface forces located at the insert surface at not a body force located in the interface region as in the previous case.

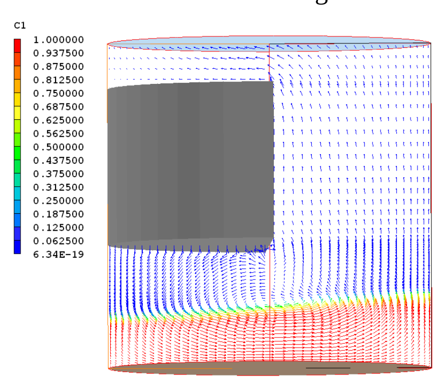
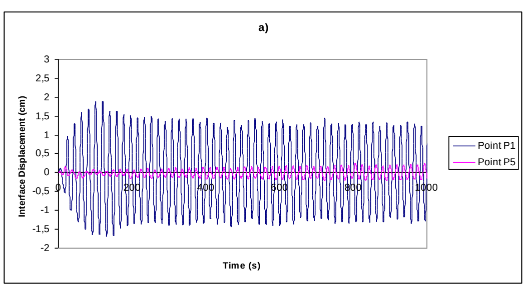


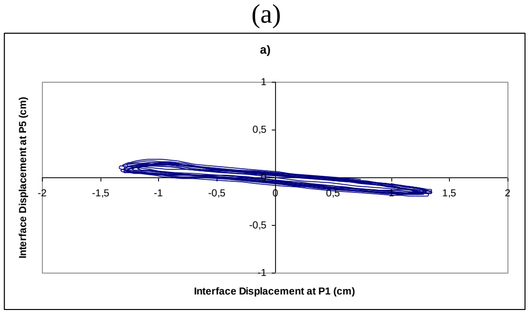
Fig. 8: Velocity vector field in the vertical plane for insert-induced motion: the shear of the interface is less than in the tank oscillations for $\sigma_f/\sigma_1 = 1.07$.

The raw times series (non filtered) of the interface displacement have been collected and are given for the first frequency of the decreasing set of frequencies (Fig. 9 (a)). The plot of the interface displacement at point 5 as a function of the interface displacement at point 1 is given for the increasing set of frequencies in Fig 9 (b) to (e) and for the increasing set of frequencies in Fig. 10 (a) to (d). The simulations are performed for the same parameters as in the previous section. The thickening of the interface (Fig. 11) is much less which tends to prove its shearing origin since the shear is much lower in this configuration (Fig 11) shows the velocity vector in the vertical plane $\theta = 0$. We note that the interface displacement for the same insert oscillation amplitude is smaller than in the experiments. The may be due to the current geometry which does not involve any free air-water free surface.

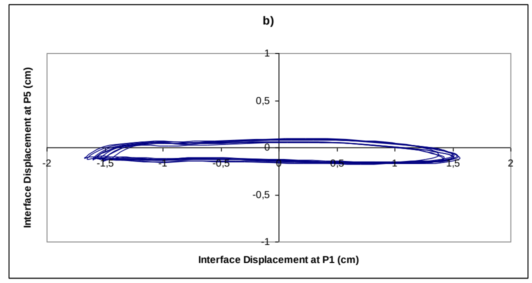
Fig. 9 (b)-(e) show that for decreasing frequencies the swirl appears for $\sigma_f / \sigma_1 = 0.96$ and looks to increase slowly with the offset to the threshold (this seems to be contradiction with the liquid-gas interface experiments) while the frequency shift decrease (what is consistent with the mentioned experiments). This seems to be contradiction with the liquid-gas interface experiments [4]. On the other hand, the swirling motion seems to exist for $\sigma_f / \sigma_1 = 0.78$ whereas experiments do not show it for this frequency. Fig. 10 (a)-(d) show that the swirl exists for the same frequencies it exists for the decreasing frequency approach to the resonance. However the detailed motion depends on the way the resonance is approached. A questioning observation is the offset position of the interface compared to its equilibrium one which is not understood up to now.



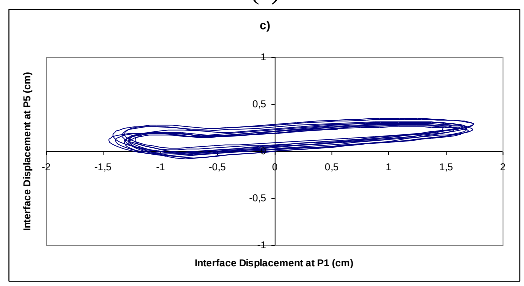
(a)



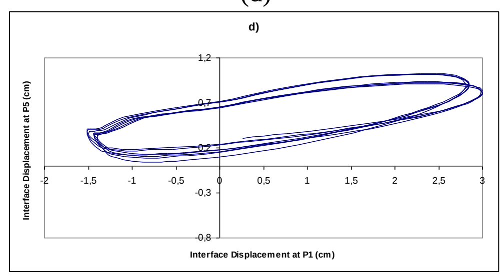
(b)



(c)

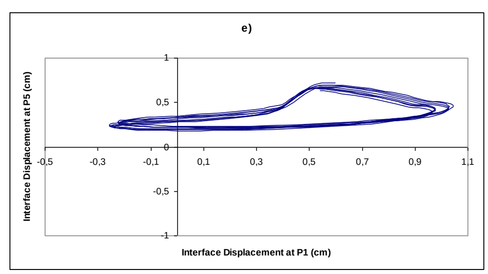


(d)

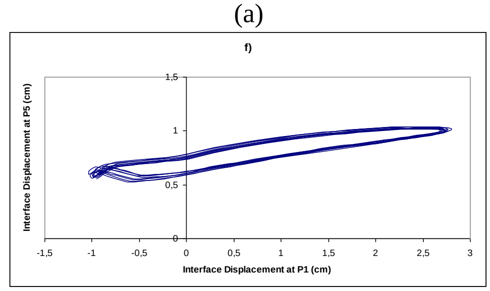


(e)

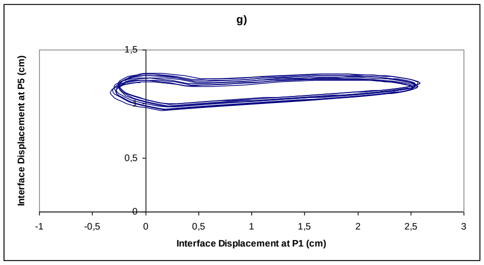
Figure 9: (a) Raw time series of the interface motion at point 5 (color)) and 1 (black) for the case $\sigma_f / \sigma_1 = 1.07$; (b) to (e): interface displacement at point 5 as a function of that at point 1 for the decreasing frequencies set.



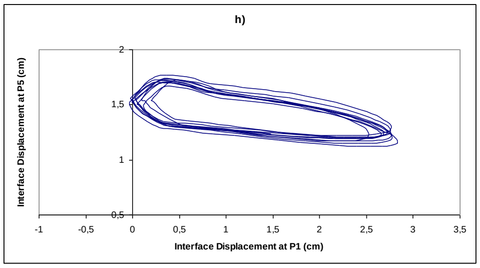
(a)



(b)



(c)



(d)

Fig 10 (a)-(d) Interface displacement at point 5 as a function of that at point 1 for the increasing frequencies set.

CONCLUSION

The numerical simulation of near resonance large amplitude motion indicates that the planar resonant internal wave bifurcates to aw swirling wave for a near-resonance frequency range. These preliminary results are in partial agreement with experiments and need to be refined. The simulation conditions must be closer to the experimental one before an extensive exploration of the phenomena is performed, including the characterization of the bifurcation, the characterization of the wave breaking scenarios.

REFERENCES

[1] A. Royon-Lebeaud, E.J. Hopfinger and A. Cartellier "Liquid sloshing and wave breaking in circular and square-base cylinder containers" JFM (2006)

[2] B. Zappoli, S. Amiroudine and S. Gautier "Instabilité de Rayleigh-Taylor dans un fluide supercritique » CRAS t.325, Série II b, 1-6 (1997)

1 [3] S. Amiroudine, J. Ouazzani, P. Carles and B. Zappoli « Numerical solution of 1-D unsteady near-critical fluid flows using finite volume methods, Eur. J; Mech. B Fluids 16, 4 (1997); G. Accary, I. Raspo, P. Bontoux, B. Zappoli, "An adaptation of the low Mach number approximation for supercritical fluid buoyant flows," C. R. Méc. **333**, 397 (2005).

[4] G.W. Wake, E.J. Hopfinger and G.N. Ivey "Experimental study on resonantly forced interfacial waves in a stratified circular cylindrical basin" Article in press JFM (2007).