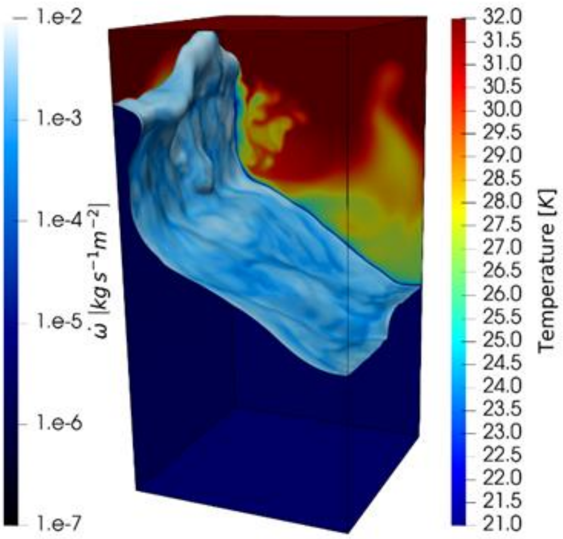
Direct numerical simulation of boil-off in sloshed cryogenic tanks

Context and mission

Numerical simulation provides a new approach to study many physical phenomena. A number of successes have been achieved, including in fluid mechanics, despite the complexity of the equations to be solved. Modelling, advances in numerical methods and computing capacity make numerical simulation in fluid mechanics a reliable tool, even in these complex regimes. Despite the intense research being carried out, there are still areas with numerous applications that have not been mastered. Heat and mass transfer near a liquid-gas interface deformed by turbulence is one of the targets that needs to be reached if we want to simulate correctly, for example, the boiling phenomenon in cryogenic tanks (boil-off), cooling and heat transfer systems in nuclear power plants or multiphase chemical reactors.

During Romain Canu's Phd (Université de Rouen, 2019), we carried out compressible two-phase simulations using a pressure-based method in the ARCHER code, where acoustic terms are implicited. As a result, we free ourselves from the constraints on the time step linked to acoustics. The interface is represented by a Coupling Level Set/Volume Of Fluid interface capturing method. Then, in the PhD of Leandro Germes Martinez (INSA Rouen, 2022), the evaporation phenomenon has been considered in this compressible formalism. These studies have been the subject of several articles [1,2], and represent major advances in the development of numerical methods dedicated to turbulent liquid-gas flows with phase change.

Recently, as part of an ANR for which I am the coordinator with CNES as a partner, we focused on simulating the phenomenon of self-pressurisation due to boiling in sloshed LH2 cryogenic tanks. In fact, the direct numerical simulations (DNS) of sloshed cryogenic tanks are of major interest for obtaining a better understanding of the physical phenomena within the tank, despite their high computational cost. The majority of studies describe the system using 0D or 1D thermodynamic budgets, which are often only valid for a static reservoir, and can rarely give unsteady profiles or local information on the variables describing the flow or thermodynamics. It is possible to carry out LES simulations of sloshed tanks, but the phase change is often considered with important approximation with constants that need to be adjusted (Lee's model for example).



With these news developments, we have been able to carry out DNS of this phenomenon and describe it accurately. A 3D simulation of a cryogenic tank subjected to sloshing represented by a sinusoidal signal has been investigated (See Figure on the left). In this context, the calculation of the convective term of the VOF and the momentum equation has been improved to ensure consistency between convections terms. In addition, this new method saves a factor of 2 in computation time. These results were presented at the EUCASS 2023 conference.

This simulation is a first step towards a better understanding of the boil-off phenomenon and the influence of the sloshing on it. However, several improvements in numerical methods are required to describe these physical phenomena more realistically.

Objectives

The aim of this thesis is to continue this work by improving the description of the thermodynamics and to analyse the results obtained using DNS of a sloshed cryogenic tank configuration under microgravity conditions. New models or corrections to existing models in the literature will be proposed, based on the DNS results obtained.

Expected results

First of all, a microgravity configuration is envisaged to match space conditions. The previous simulation incorporated gravity. In microgravity conditions, the liquid-solid contact angle must be properly considered because it can have an influence on the flow. The implementation of a low contact angle is envisaged for the forthcoming thesis, corresponding to a cryogenic fluid contact angle. In addition, we would like to carry out a parametric study with different heat fluxes entering the tank to evaluate different pressurisation regimes.Further validation of the thermodynamics is also required: we plan to integrate real fluid-type equations of state (e.g. Peng Robinson equation). This change may introduce changes in the compressible formalism, but will provide a better description of thermodynamic equilibria, particularly at the liquid-gas interface. New validations will be carried out during the thesis on this aspect.Finally, we plan to study and propose corrections to the phase change models frequently used in these configurations (Lee or Schrage model) based on the DNS database. Depending on the results obtained, it may also be possible to propose a new phenomenological models, better suited to LES/RANS simulations.

This work will be presented in international conferences (in multiphase flows and cryogenic community) and published in A rank journals.

Working environment

The CORIA laboratory is well known internationally for its expertise in combustion, turbulence, multiphase flows and optics.

Our group is within the multiphase flows department where we have a small group of PhD student and 3 permanents researchers (F.X. Demoulin, J. Reveillon, B. Duret) that will be happy to welcome you.

This PhD is cofunded by CNES (Central National d'Etudes Spatiales - Direction Technique et Numérique) which will also manage this PhD and will demand a number of report during the PhD. The CNES also give the opportunity to the PhD student to visit the Salon du Bourget at Paris, attend the young researcher day from CNES at Toulouse and other events.

Candidate profile

The applicant should justify a research cursus: Master degree (Bac+5) or Engineering school. His CV should show an academic or professional experience in the energetic domain, fluid mechanics and/or numerical simulation, applied mathematics, and also have programming skills (fortran, python).

Salary is expected to be around 2200 € gross per month. Can be more if you want to do some teaching.

[1] L.G. Martinez et al. A new DNS formalism dedicated to turbulent two-phase flows with phase change, IJMF. 143 (2021) 103762.

[2] L.G. Martinez, et al., Vapor mixing in turbulent vaporizing flows, IJMF. 161 (2023) 104388.