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# CFD modelling of the non-isobaric evaporation of cryogenic liquids in storage tanks

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Cryogens, such as liquefied natural gas or liquid hydrogen, are conventionally stored in highly insulated tanks. These tanks are susceptible to heat transfer from the surrounding environment. The temperature difference between the ambient air and the cryogen inside the tank drives this heat transfer, leading to cryogen heating and evaporation. As the cryogen continuously evaporates, the pressure inside the tank gradually rises—a phenomenon known as self-pressurization. When the tank reaches its maximum allowable working pressure (MAWP), excess evaporated cryogen is released as a boil-off gas (BOG). Proper management of BOG is essential to mitigate safety and environmental risks and minimize economic losses due to the gradual loss of stored cryogen over time. Despite the development of several models for non-isobaric cryogen evaporation, none of them consistently achieve accurate predictions for pressure, liquid, and vapor temperature profiles across a practical range of applications.

This research presents a new CFD model relevant to non-isobaric cryogen evaporation. The model considers the heat influx from the surroundings to the liquid and vapour phases, and the heat transfer between the phases. The phase change sub-model considers two contributions: an interfacial energy balance far from the tank wall and direct wall-to-liquid conduction near the wall. The model comprises a new single-phase CFD model for the liquid phase and a 1-D model for the vapour phase. The CFD model has been implemented in the open-source computational fluid dynamics toolbox OpenFOAM to facilitate its reproducibility.

The model provides detailed information on liquid and vapour temperature profiles, liquid velocity profiles, pressure build-up, and evaporation rates. Below the vapor-liquid interface, liquid natural convection is dampened by thermal stratification. This stratification occurs due to an increase in the interfacial temperature caused by rising pressure. As pressure increases, the temperature gradient below the interface dampens liquid phase natural convection in this region. Above the tank bottom, vortical currents emerge as a result of natural convection driven by bottom heating. These currents play a crucial role in mixing the liquid phase, which explains the reduced levels of liquid thermal stratification in scenarios with low liquid filling. Additionally, the model highlights that the pressure build-up is primarily governed by vapour heating, particularly during the initial stages of evaporation.

The model was used to analyse liquid velocity profiles for two sets of experimental data for the evaporation of liquid nitrogen. Two empirical parameters, namely the wall heat partitioning fraction and the overall heat transfer coefficients, were fitted to represent experimental uncertainty on wall heat ingress. The results show that most external vapour heat ingress does not reach the vapour phase bulk. Instead, it is transported downwards through the walls and transferred to the liquid at the liquid-vapour-wall contact point, driving phase change. Heat conduction from the walls to the interface has a significant effect, even for low heat fluxes, and cannot be neglected.

The developed model requires simulation times three orders of magnitude lower than a full multiphase CFD model. It is thus seen as an efficient tool that can aid the optimisation of the design and operation of cryogenic storage tanks. The model can simulate cryogen evaporation in large-scale storage tanks using parallel processing by changing only the input dictionaries. Similarly, it is directly applicable to any tank that presents axial symmetry and is easily extended to arbitrary geometries. For long-term cryogen storage involving pressurisation and boil-off gas removal cycles, the model can be fitted to a single pressurisation cycle and used to predict future cycles.

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