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Thermodynamic Modeling of Cryogenic Fuel Tanks with a Model-Based Inverse Method

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Abstract : Cryogenic fuels such as Liquid Hydrogen (LH_2) must be transported and stored at extremely low temperatures. Without expensive active cooling solutions, preventing fuel boil-off over time is impossible. Hence, one must resort to venting systems at the cost of significant energy and fuel mass loss. These losses increase significantly in propellant tanks installed on vehicles, as the presence of external accelerations induces sloshing. Sloshing increases heat and mass transfer rates and leads to significant pressure oscillations, which might further trigger propellant venting. To make LH_2 economically viable, it is essential to minimize these factors by using advanced control techniques. However, these require accurate modelling and a full understanding of the tank's thermodynamics. The present research aims to implement a simple thermodynamic model capable of predicting the state of a cryogenic fuel tank under different operating conditions (i.e., filling, pressurization, fuel extraction, long-term storage, and sloshing). Since this model relies on a set of closure parameters to drive the system's transient response, it must be calibrated using experimental or numerical data. This work focuses on the former approach, wherein the model is calibrated through an experimental campaign carried out on a reduced-scale model of a cryogenic tank. The thermodynamic model of the system is composed of three control volumes: the ullage, the liquid, and the insulating walls. Under this lumped formulation, the governing equations are derived from energy and mass balances in each region, with mass-averaged properties assigned to each of them. The gas-liquid interface is treated as an infinitesimally thin region across which both phases can exchange mass and heat. This results in a coupled system of ordinary differential equations, which must be closed with heat and mass transfer coefficients between each control volume. These parameters are linked to the system evolution via empirical relations derived from different operating regimes of the tank. The derivation of these relations is carried out using an inverse method to find the optimal relations that allow the model to reproduce the available data. This approach extends classic system identification methods beyond linear dynamical systems via a nonlinear optimization step. Thanks to the data-driven assimilation of the closure problem, the resulting model accurately predicts the evolution of the tank's thermodynamics at a negligible computational cost. The lumped model can thus be easily integrated with other submodels to perform complete system simulations in real time. Moreover, by setting the model in a dimensionless form, a scaling analysis allowed us to relate the tested configurations to a representative full-size tank for naval applications. It was thus possible to compare the relative importance of different transport phenomena between the laboratory model and the full-size prototype among the different operating regimes.

Keywords : destratification, hydrogen, modeling, pressure-drop, pressurization, sloshing, thermodynamics
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