Analyses of Cryogenic Propellant Tank Pressurization based upon Experiments and Numerical Simulations

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In the recent decade, aerospace industry put great effort in increasing the payload mass of launcher by concurrently decreasing the launcher mass itself. Therefore cryogenic upper stages got back into focus, since they offer an increased payload capacity due to the very high specific impulse of their engines. Against this background, interest in the advancement of cryogenic propellant management technologies has been significantly revived.

One important subsystem of the cryogenic propellant management system is the pressurization system. It is part of the feed system and provides a pressurant gas to expel the liquid, cryogenic propellants from the tanks. Due to the very low liquid temperatures, complex fluid-dynamic and thermo-dynamic processes occur during pressurization inside the propellant tank, which are not yet fully understood. Since tank pressurization requires on-board resources as pressurant gas, optimization of the pressurization process is important in order to lower the launcher mass. The motivation of this study is to further the knowledge about thermodynamic and fluid-dynamic effects during the active-pressurization process of a cryogenic propellant tank in order to optimize the on-board pressurant gas mass. Therefore, data from ground experiments, numerical simulations, and theoretical approaches were applied.

At first, the experimental set-up, consisting of a partially filled liquid nitrogen tank, pressurized either with gaseous nitrogen or gaseous helium, as well as the test procedure is briefly introduced. Afterwards, the experimental results for the pressure and temperature evolution during and after active-pressurization are presented and compared to numerical calculations. Moreover, the pressurant gas mass, required to reach the final pressure level, was analyzed with respect to the pressurant gas type and its inlet temperature. The experimental results were compared to results of numerical simulations. Furthermore, due to theoretical and numerical considerations, the phase change during and after pressurization was analyzed. Along with this, an assessment of the heat flows, entering the tank and its further distribution inside the tank and the fluids is presented. Consequently, the evolution of the thermal stratification in the liquid and vapor phase during and after the pressurization is evaluated. The experimental data was compared to analytical heat transfer models, in order to identify the dominating heat transfer mechanisms. Finally, the pressure drop after the pressurization end was analyzed. Therefore, the experimental data were compared to results of an analytical pressure drop model and numerical simulations.

This paper describes in detail the results of the performed active-pressurization experiments, numerical simulations, and theoretical approaches and presents conclusions drawn from these results.