CFD Analysis of Noncondensable Gas Effects on Zero-Boil-Off Self-Pressurization and Pressure Control of a Two-Component Volatile Fluid: 1G Validation & Microgravity Predictions

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In future refueling depot and space operations, noncondensable gases (NCG)s may be used as pressurants to extract liquid propellant for tank-to-tank transfer and engine start-up operations. Once in the ullage, the noncondensable gas can affect the interfacial evaporation and condensation processes that control tank self-pressurization and pressure control during subsequent storage. The Zero-Boil-Off-Tank-Noncondensable (ZBOT-NC) Experiment and its associated computational model development effort are carried out to study these phenomena.

In this work, we present a Sharp Interface CFD (SI-CFD) model which is applied to the two-phase and two-component simulant fluid system used in the ZBOT-NC Experiment with Perfluoro-n-Pentane (PnP) as the *simulant* low-boiling point phase change fluid, and Xenon as the noncondensable gas. The SI-CFD model solves the continuity, momentum, energy, species, and turbulence equations in the vapor and liquid phases while providing very accurate temperature and species gradient calculations at the interface. Particular attention was focused to correctly predict the vapor "Stefan wind" in the ullage, as well as the extent of the accumulation of the noncondensable gas at the phase front.

The CFD model is validated first against existing 1g data for LH2/GHe tank pressure control. Detailed microgravity and 1g numerical simulations and analyses performed for ZBOT-NC are also presented to show the characteristics of the NCG-induced transport resistance in the ullage, along with the thermocapillary (Marangoni) convection that is generated in the liquid and their impact on the interfacial heat and mass transfer during tank self-pressurization and jet mixing pressure control. Simulations results indicate that, in 1g, the presence of the noncondensable gas affects the pressure control noticeably but its impact on self-pressurization is minimal. However, in microgravity, the noncondensable gas seems to have a noticeable impact during self-pressurization while its effect on jet mixing pressure control is significant and considerably more pronounced than on earth.