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A COMBINED CFD/DSMC/FREE MOLECULAR ANALYSIS OF MICROSCALE LEAKS IN SPACE VEHICLES

Abstract

Small leaks from space vehicles are of major concern during long-duration extra-planetary missions. Microscale leaks, though undetectable by short term pressure measurements, can cause substantial loss of valuable cargo, unexpected thrust and structural damage.

Leaks are currently detected through the use of handheld acoustic detection devices that can prove problematic when attempting to detect material of an unknown type being ejected from a crack of unknown size and shape into space. Substantial research is being performed to detect such mission-endangering leaks using methods such as Michelson interferometers to measure density changes due to leaking materials, ultrasonic arrays to detect spacecraft skin cracks, and fiber optic microsensors for chemical-specific detection. However, current sensor techniques are limited by the localization of sensors, the material being released, and background noise from the space vehicle.

The objective of this research is to better understand how to detect micro-scale vehicular leaks through a combined Computational Fluid Dynamics(CFD)/Direct Simulation Monte Carlo(DSMC)/Free Molecular fluidic analysis formulated to better quantify measureable effects of these leaks. Due to the extreme density gradient found in such flows, the flow field must be solved with a multi-physics solver that applies three distinct physical models: an initial high density continuum region, a medium density DSMC region, and a ray-tracing free molecular region. The leaking material is assumed to start from a zero-gravity stagnation source and is expelled into a vacuum through a variety of openings, changing from continuum mechanics to particle mechanics as the flow rarefies.

Patching between dense and rarefied zones is performed using ghost cells which exchange continuum and particle data across equivalent overlapping cells to ensure solution consistency. Model regions are chosen through calculation of the Knudsen number, which compares intermolecular interaction scales to the scales of the flow field. Air, oxygen, hydrogen, argon, water and cryogenic fuels are tested by altering diffusion and particle collision parameters. Quantities of interest include, but are not limited to, the rate of mass loss, force on the space vehicle, stress on the exterior skin, localized heating/cooling effects and acoustic characteristics of the micro-leak. The impact of micro-leaks on external structures is also examined. The effect of breach size, shape, material type and source pressure is analyzed to determine the most easily detectable features of vehicular micro-fractures.