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C1Po2A-03: Experimental investigation of fast chill-down performance in cryogenic transfer lines using wire coil inserts

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The demand for highly efficient chill-down technologies for transfer lines and storage tanks of cryogenic propellant systems in future space mission has intensified in recent years. To ensure successful and reliable operation of the propellant system, it is necessary to achieve high liquid loading in the tanks, which requires a vapor-free flow in the transfer line. The high temperature difference between cryogenic fluid and its surroundings, however, leads to valuable propellant loss due to boil-off. To minimize this loss, a chill-down process is required to cool the transfer line to a desired cryogenic temperature. The line chill-down process is characterized by unsteady two-phase flow, which occurs sequentially in three distinct regimes: vapor film boiling, transition boiling and nucleate boiling regime. The chill-down process is overwhelmingly dominated by the less efficient vapor film boiling regime, in which a vapor film separates a liquid core from the wall. Therefore, the key to achieving a faster chill-down and minimizing propellant usage is promoting the fast transition from the vapor film boiling to the transition boiling regime.

Heat transfer augmentation techniques can be simply classified into two types: passive and active methods. Active techniques require additional external power to operate, whereas passive techniques involve modifications to the system configuration, such as extended or specially treated surface, inserts, and porous materials, etc., to enhance heat transfer without the additional external power. In aerospace applications, where power saving and maintenance are crucial factors, passive methods are more suitable than active ones. Among the various types of passive techniques, wire coil inserts are known for their excellent design flexibility. Wire coils can be an optimal solution for achieving efficient chill-down, especially considering the wide variability of propellant transfer line configuration and mass flow rate across different systems and their operating scenario.

This study aims to examine the effectiveness of wire coil inserts in enhancing the heat transfer of cryogenic transfer lines for rapid chill-down. Liquid nitrogen (LN2) is used as a test fluid and circular cross-sectioned wire coil inserts with five different pitch-to-diameter ratios (p/D = 0.47, 0.75, 0.93, 1.12, 1.40) are explored. The chill-down experiment is conducted for stainless steel tube in vertical orientation under various mass flow rates. The experimental apparatus comprises a liquid supply section, test section, and vaporizing section. The thermodynamic state of the fluid is monitored in the liquid supply section to ensure that the liquid-phase fluid flows into the test section. In the test section, a test tube is insulated using foam rubber to minimize parasitic heat in-leak from the ambient environment. Temperatures are measured at multiple locations along the tube wall using E-type thermocouples for thermal characterization, while pressures at the inlet and outlet of the test section are measured for pressure drop calculation. It has been experimentally observed that the wire coil inserts cause a substantial enhancement in chill-down efficiency and in turn significantly reduce the chilldown time by more than 1/5 in comparison to the smooth tubes. This is achieved by promoting mixing and breaking down the vapor film, and thereby facilitating the transition from the vapor film boiling to the transition boiling regime. This finding is of significant importance as it suggests a fast chill-down method that can effectively reduce the chill-down time for various systems with different configuration and mass flow rates.

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