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Investigation on Efficient Cooling Methods for Cryogenic Fluid Pipelines

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Cryogenic fluids, boasting diverse industrial applications, play a pivotal role in cutting-edge technologies. Notably, liquid helium (LHe) serves the purpose of cooling Earth-orbiting telescopes and satellites, while liquid hydrogen (LH2) plays a crucial role in the cooling of superconducting magnets and propelling space engines. Prior to achieving the efficient flow of cryogenic fluids, the necessary cooling of transfer lines and associated hardware to temperatures below the fluid's saturation point is imperative. The predominant method for heat dissipation involves employing the cryogenic fluid itself to quench the transfer system. However, the distinctive properties of cryogenic fluids, characterized by exceedingly low surface tension, standard boiling points, and kinematic viscosity, pose considerable challenges in maintaining effective cooling along transport lines, which traverse through diverse boiling regimes such as film, transition, and nuclear boiling. The selection of an appropriate cooling method for transportation lines demands meticulous consideration of trade-offs related to cooling efficiency, refrigerant consumption, and system complexity. This investigation introduces a robust three-dimensional model designed for simulating unsteady heat transfer and gas-liquid two-phase flow within LH2 pipelines. Rigorous validation against experimental data attests to the fidelity of the simulation results. Throughout the cooling cycle, the pipeline undergoes transitions in flow, including stratified smooth, wavy, and intermittent flows. Due to the extremely low liquid-to-gas density ratio and surface tension of hydrogen, the gas-liquid interface exhibits pronounced fluctuations, and the wavy flow dominates throughout the pipeline. A comprehensive comparative analysis of three cooling modes is conducted: constant flow, variable flow, and pulsating flow, focusing on key performance parameters such as flow rate, temperature, heat transfer coefficient, pressure drop, cooling time and hydrogen consumption. In conclusion, an evaluative framework for distinct pipeline cooling modes is proposed: a reasonable variable flow cooling mode exhibits certain advantages in both cooling time and liquid hydrogen consumption when compared with the constant flow cooling mode. A high flow rate in the initial stage facilitates rapid cooling, while the subsequent trickling flow in the middle stage proves conducive to conserving liquid hydrogen consumption. The pulse flow cooling method adeptly capitalizes on the performance benefits derived from intermittent flow. Specifically, within the cooling range of 40 K to 20 K, it substantially economizes liquid hydrogen consumption (15%-20%), albeit concomitant with an extended total cooling time (40%-60%). This study endeavors to conduct a thorough assessment of diverse cooling modes, offering theoretical insights to guide the high-efficiency cooling of cryogenic fluid pipelines.

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