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Computational Modeling of Density Wave Instability in Cryogenic Hydrogen

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Extended Abstract

Hydrogen is a promising renewable and clean energy carrier that can help humanity impede the catastrophic climate change. To be used as a fuel for long-range heavy-duty transportation means, hydrogen needs to be stored and transported in the energy-dense liquid form. This requires very low cryogenic temperatures as liquid hydrogen boils at around 20 K. When transferring liquid hydrogen, the heat leak into pipe lines can cause boiling of hydrogen and formation of two-phase flow. Such a multiphase flow is prone to instabilities [1], including density wave oscillations [2,3], which complicate hydrogen transfer and increase thermal and mechanical fatigue of the system. These oscillations are caused by dynamic coupling between heat addition, flow inertia, phase change, and fluid compressibility, with a major role played by increase of friction in a two-phase flow relative to a single-phase flow.

In this study, the one-dimensional unsteady equations of continuity, momentum, and energy are applied to model hydrogen flow boiling in a pipe with heat addition. The fluid mechanics equations are numerically solved using a finite difference method on a staggered grid with an implicit upwind scheme and an iterative solver, while assuming homogeneous equilibrium flow. The parahydrogen properties from REFPROP software [4] are utilized. With liquid hydrogen present in the initial state, the nonlinear governing equations are integrated in time to determine whether the flow converges to a steady solution or results in limit-cycle oscillations.

As no test data currently exist for density wave oscillations in hydrogen, the validation of present model is demonstrated using experimental results available for two-phase Freon-113 flow [5] for transition to instability in a system with given geometry, mean pressure, initial subcooling, flow rate, and supplied heat. Then, time-domain behaviour of the system properties (inlet and outlet flow rates, pressure recorded at several points, and exit quality) is presented for both stable and unstable cases in the setup with cryogenic hydrogen. Examples of dependences of amplitudes of the same metrics on the rate of supplied heat are given as well. Finally, stability boundaries in the system with liquid hydrogen are shown in commonly used non-dimensional parameters, the subcooling number and the phase change number, which depend on the fluid properties, supplied heating power, and mass flow rate. The results obtained in this work are useful for designers and operators of liquid hydrogen transfer lines and other systems with cryogenic flows.

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