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C3Po1C-06: Three-dimensional simulations for evolving thermodynamic scaling laws in cryogenic cavitating fluid transients

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Cavitating fluid transients occur when sudden changes in flow, such as rapid acceleration or deceleration, cause significant pressure variations in a pipeline. These variations generate oscillatory pressure waves, leading to the formation and collapse of vapour cavities when the pressure during the rarefaction wave drops below the vapour pressure. During collapse, these cavities can emit high-pressure acoustic waves, resulting in significant pressure fluctuations. Such oscillations may exceed safe operating limits, posing risks of permanent damage to equipment and disrupting the flow operations of the fluid networks. In cryogenic systems, this phenomenon becomes even more complex due to the extremely low operating temperatures, significant variations in thermophysical properties, and the thermosensitive nature of cryogenic fluids. Cavitation in cryogenic flows is strongly influenced by the latent heat drawn from the bulk fluid, leading to a significant decrease in its temperature and thermal boundary layer formation, eventually resulting in the thermal delay or suppression of cavitation. Also, studying these cryogenic fluid transient events experimentally is challenging and expensive due to the need for strict thermal insulation to prevent heat in-leak.

This study presents detailed three-dimensional numerical simulations performed using Ansys Fluent for cavitating fluid transients in cryogenic pipelines triggered by the rapid closure of a valve. Existing cavitation models are evaluated and compared to analyse key flow features, including pressure fields, velocity fields, and vapour distribution. These simulations offer insights into the interaction of fluid dynamics and thermodynamic effects, which are critical for the design of cryogenic flow networks, such as the cryogenic propellant management systems used in rocket engines. To address the limitations of existing cavitation models, we identify gaps in their predictive capabilities and propose a modified cavitation model tailored to cryogenic fluid conditions. Furthermore, thermodynamic scaling techniques are developed, including the formulation of a novel non-dimensional number to characterize cavitating cryogenic fluid transients. Using this scaling approach, we determine the operating temperature at which an alternative fluid exhibits similar cavitation behavior as cryogenic fluids. Finally, three-dimensional simulations are performed for the alternate fluid at the identified temperature, and the results are compared with cryogenic fluid simulations to validate the scaling methodology. The results suggest an approach of replacing cryogenic fluids with a surrogate fluid under scaled conditions to mimic similar cavitation behaviour and resulting effects, making experimental studies more feasible. This comprehensive study enhances the understanding of cavitating transients in cryogenic pipelines, which will help design the scaled experimental setup with thermodynamically similar fluid and improve the safety and reliability of cryogenic systems.

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