

Development of a Numerical Analysis Method for the Subcooling of Liquid Hydrogen Induced by Helium Injection

Toshiki Nara ¹⁾ Haruka Nikado ¹⁾ Gen Fujiura ¹⁾ Hideyoshi Takashima ¹⁾ Masaharu Uchiumi ²⁾

1) AIS Hokkaido Inc.

1-1-2 kita 7-jo Nishi 1-chome, kita-ku, Sapporo-shi, Hokkaido, 060-0807, Japan (toshiki_nara@ais-hokkaido.co.jp)

2) Muroran Institute of Technology

27-1 Mizumoto-cho, Muroran-shi, Hokkaido, 050-8585, Japan

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Cryogenic fuels such as liquid hydrogen require efficient subcooling to enhance the energy density of the fuel stored in tanks. Helium injection is one of the subcooling methods. Injecting helium into liquid hydrogen causes the liquid to evaporate, which lowers the liquid's temperature through latent heat. In this study, we developed a computational fluid dynamics (CFD) analysis method that models evaporation phenomena to enable a more detailed evaluation of subcooling.

In helium injection subcooling, hydrogen evaporates into the injected helium bubbles in liquid hydrogen (LH₂), and the vapor diffuses into the bubbles. Evaporation continues until the bubbles reach saturation, and remove heat from the surrounding liquid through the latent heat of vaporization. Accurately modeling this phenomenon requires the simultaneous consideration of multiphase flow, phase change, vapor concentration within the bubbles, and heat transfer. The numerical analysis was performed using a customized version of icoReactingMultiphaseInterFoam, an open-source solver available in OpenFOAM. The source code was modified to improve the conservation of volume, mass, and energy. The diffusionGasEvaporation model was employed to simulate evaporation, while the Antoine equation was used to calculate the saturation vapor pressure. The evaporation rate is calculated based on Fick's law using the saturation partial pressure and the vapor mass fraction inside the bubble.

A simplified system containing a single helium bubble in LH₂ was analyzed to validate the numerical model. The initial bubble shape was assumed to be spherical, with diameters ranging from 1 mm to 20 mm. The initial temperature of the bubble was set equal to that of the surrounding LH₂ so that the analysis could focus exclusively on the temperature decrease caused by evaporation. By visualizing the simulation results, it was confirmed that the shape of a rising bubble changes depending on its diameter. The analysis also revealed differences in the evaporation behavior at the bubble interface and in the cooling characteristics of the surrounding fluid caused by latent heat absorption. These findings improve the understanding of the cooling mechanism associated with helium injection and provide valuable insights for the development of more efficient cooling methods.

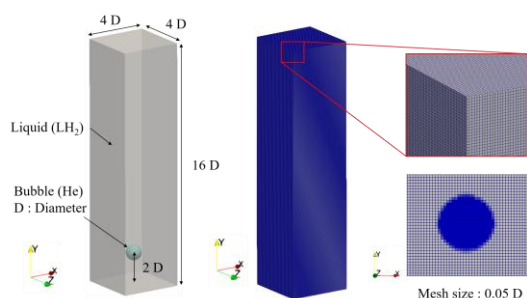


Fig.1 Analysis model

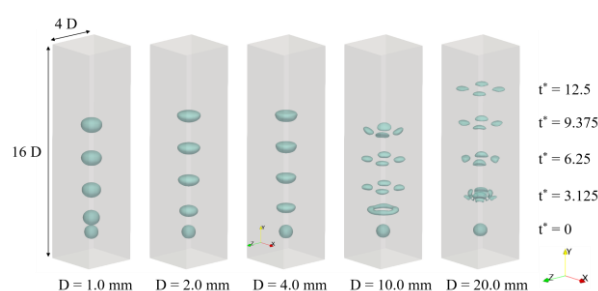


Fig.2 Deformation history of a bubble

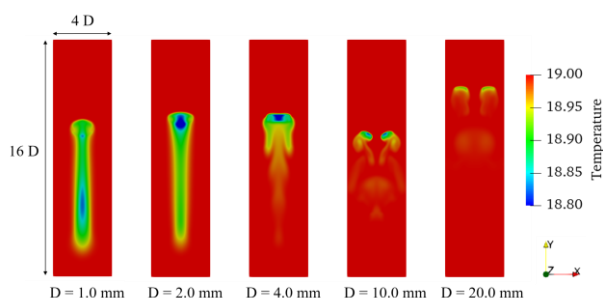


Fig.3 Visualization of temperature

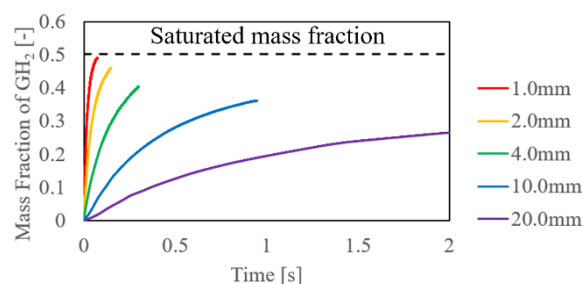


Fig.4 Mass fraction of GH2 in a bubble